



**ACHARYA N.G. RANGA AGRICULTURAL UNIVERSITY**

Course No. **FDEN-223**  
Course Title: **Food Processing Equipment - I**  
Credits: **3 (2 + 1)**

**Prepared by**

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**DEPARTMENT OF FOOD ENGINEERING**

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|---|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1 | Course No                                                                                                                                                                      | : | <b>FDEN - 223</b>                                                                                                                                                                                                                                                                                                                                                                                 |
| 2 | Title                                                                                                                                                                          | : | <b>Food Processing Equipment-I</b>                                                                                                                                                                                                                                                                                                                                                                |
| 3 | Credit hours                                                                                                                                                                   | : | <b>3 (2+1)</b>                                                                                                                                                                                                                                                                                                                                                                                    |
| 4 | General Objective                                                                                                                                                              | : | To impart knowledge to the students on principles, operation and maintenance of various food processing equipments namely material handling equipment, cleaning, grading, sorting, mixing, forming, size reduction, centrifugation, filtration, evaporation, drying, cutting and grinding equipments.                                                                                             |
| 5 | Specific Objectives                                                                                                                                                            | : |                                                                                                                                                                                                                                                                                                                                                                                                   |
|   | a) Theory                                                                                                                                                                      | : | By the end of the course, the students will be able to<br>i) understand different food processing equipments that are being used in food industries<br>ii) study about the principles, operation and maintenance of food processing equipments viz., material handling, cleaning, grading, mixing, forming, size reduction, cutting, grinding, centrifugation, filtration, evaporation and drying |
|   | b) Practical                                                                                                                                                                   | : | By the end of the course, the students will be able to<br>i) determine the Engineering properties of food materials<br>ii) solve design problems on heat exchangers and<br>iii) determine overall heat transfer co-efficient of heat exchangers                                                                                                                                                   |
|   | <b>A) THEORY LECTURE OUTLINES</b>                                                                                                                                              |   |                                                                                                                                                                                                                                                                                                                                                                                                   |
| 1 | INTRODUCTION TO MATERIAL HANDLING AND TRANSPORTATION - SELECTION OF MATERIAL HANDLING MACHINES AND CONVEYORS, BELT CONVEYOR; BELT CONVEYOR IDLERS, IDLER SPACING, BELT TENSION |   |                                                                                                                                                                                                                                                                                                                                                                                                   |
| 2 | BUCKET ELEVATOR: HEAD SECTION, BOOT SECTION, ELEVATOR LEGS, ELEVATOR BELTS, BUCKETS, DRIVE MECHANISM, HP REQUIREMENT                                                           |   |                                                                                                                                                                                                                                                                                                                                                                                                   |
| 3 | SCREW CONVEYOR: SCREW CONVEYOR DETAILS, VARIOUS SHAPES                                                                                                                         |   |                                                                                                                                                                                                                                                                                                                                                                                                   |

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|----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|    | OF SCREW CONVEYOR TROUGH, CAPACITY AND HORSE POWER                                                                                                                                                    |
| 4  | PNEUMATIC CONVEYOR, LIMITATIONS OF PNEUMATIC CONVEYING, CHAIN CONVEYOR                                                                                                                                |
| 5  | PRETREATMENT UNIT OPERATIONS : CLEANING, SORTING: FIXED APERTURE SORTING                                                                                                                              |
| 6  | SORTING: VARIABLE APERTURE SCREENS, IMAGE PROCESSING, COLOR SORTING, WEIGHT SORTING AND GRADING                                                                                                       |
| 7  | PEELING, DEHULLING, DEHUSKING                                                                                                                                                                         |
| 8  | MIXING : INTRODUCTION, AGITATION, AGITATED VESSELS, MIXING OF LIQUIDS                                                                                                                                 |
| 9  | MIXING OF SOLIDS: EQUIPMENT- RIBBON BLENDER, KNEADER, DOUBLE CONE MIXER, TUMBLING MIXERS, DOUGH AND PASTE MIXERS                                                                                      |
| 10 | FORMING-BREAD MOULDERS, PIE AND BISCUIT FORMERS, CONFECTIONERY MOULDERS                                                                                                                               |
| 11 | SIZE REDUCTION:INTRODUCTION, GRINDING AND CUTTING, ENERGY USED IN GRINDING, KICK'S LAW, RITTINGER'S LAW, BOND'S LAW                                                                                   |
| 12 | EQUIPMENT FOR SIZE REDUCTION: CUTTERS & GRINDERS, CRUSHERS, GYRATORY CRUSHER, HAMMER MILL, BALL MILL, TUMBLING MILL                                                                                   |
| 13 | SEPARATION BY CENTRIFUGATION AND FILTRATION                                                                                                                                                           |
| 14 | SEPARATION BY EXPRESSION, EXTRACTION USING SOLVENTS                                                                                                                                                   |
| 15 | MEMBRANE CONCENTRATION                                                                                                                                                                                |
| 16 | INTRODUCTION AND IMPORTANCE OF PHYSICAL PROPERTIES-SHAPE AND SIZE OF GRAINS, SHAPE AND SIZE OF FRUITS, BULK DENSITY OF THE GRAINS, TRUE DENSITY OF THE GRAINS, POROSITY, ANGLE OF REPOSE, TEST WEIGHT |
| 17 | CO-EFFICIENT OF EXTERNAL FRICTION, CO-EFFICIENT OF INTERNAL FRICTION, COLOUR OF FOOD MATERIALS                                                                                                        |
| 18 | THE NEED TO CONSIDER HYGIENIC DESIGN, HAZARDS, HOW TO APPROACH HYGIENIC DESIGN, HYGIENIC DESIGN PRIORITIES, HYGIENIC DESIGN PRINCIPLES, SOME GENERAL DESIGN POINTERS                                  |
| 19 | SOME BASIC CONCEPTS OF RHEOLOGY, BIOLOGICAL SYSTEMS AND MECHANICAL PROPERTIES, ASTM STANDARD DEFINITION OF TERMS                                                                                      |

|    |                                                                                                                                                                                      |
|----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|    | RELATED TO MECHANICAL PROPERTIES                                                                                                                                                     |
| 20 | OTHER DEFINITIONS RELATED TO MECHANICAL PROPERTIES                                                                                                                                   |
| 21 | PHYSICAL STATES OF A MATERIAL, CLASSICAL IDEAL MATERIALS, IDEAL ELASTIC BEHAVIOR (HOOKEAN BODY), IDEAL PLASTIC BEHAVIOR (ST. VENANT BODY), IDEAL VISCOUS BEHAVIOR (NEWTONIAN LIQUID) |
| 22 | RHEOLOGICAL MODELS, ELECTRICAL EQUIVALENCE OF MECHANICAL MODELS                                                                                                                      |
| 23 | RHEOLOGICAL EQUATIONS                                                                                                                                                                |
| 24 | AERO AND HYDRODYNAMIC PROPERTIES, DRAG COEFFICIENT AND TERMINAL VELOCITY                                                                                                             |
| 25 | EVAPORATION, BOILING POINT ELEVATION, TYPES OF EVAPORATORS, BATCH TYPE PAN EVAPORATOR, NATURAL CIRCULATION EVAPORATORS                                                               |
| 26 | RISING FILM EVAPORATOR, FALLING FILM EVAPORATOR, RISING AND FALLING FILM EVAPORATOR, FORCED-CIRCULATION EVAPORATOR PLATE EVAPORATOR                                                  |
| 27 | DESIGN OF A SINGLE EFFECT EVAPORATOR, MATERIAL AND ENERGY BALANCES, EVAPORATOR EFFICIENCY, BOILING POINT ELEVATION, METHODS OF IMPROVING EVAPORATOR EFFICIENCY                       |
| 28 | SIZING OF MULTIPLE EFFECT EVAPORATORS                                                                                                                                                |
| 29 | THIN LAYER DRYING, MOISTURE CONTENT, EQUILIBRIUM MOISTURE CONTENT, HYSTERESIS, DRYING CURVES, CONSTANT - RATE PERIOD, FALLING - RATE PERIOD                                          |
| 30 | TRAY AND CABINET DRYER, TUNNEL DRYER, PUFF-DRYING, FLUIDIZED - BED DRYING, SPRAY DRYING, FREEZE - DRYING                                                                             |
| 31 | INTRODUCTION TO HEAT PROCESSING - BLANCHING, PASTEURIZATION, STERILIZATION                                                                                                           |
| 32 | KINETICS OF MICROBIAL DEATH, DECIMAL REDUCTION TIME AND THERMAL RESISTANCE CONSTANT, PROCESS LETHALITY                                                                               |

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|   | <b>B) Practical Class Outlines</b>                                     |
| 1 | Determination of engineering properties of food materials              |
| 2 | Study of Plate type of heat exchangers used in Dairy and Food Industry |

|    |                                                                                                                                                     |
|----|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| 3  | Study of Shell and Tube type of heat exchangers used in Dairy and Food industry                                                                     |
| 4  | Determination of thermal conductivity of milk, solid dairy and food products                                                                        |
| 5  | Determination of overall heat transfer co-efficient of Shell and tube, Plate heat exchangers, Jacketed kettle used in Dairy and Food Industry - I   |
| 6  | Determination of overall heat transfer co-efficient of Shell and tube, Plate heat exchangers, Jacketed kettle used in Dairy and Food Industry - II  |
| 7  | Determination of overall heat transfer co-efficient of Shell and tube, Plate heat exchangers, Jacketed kettle used in Dairy and Food Industry - III |
| 8  | Studies on heat transfer through extended surfaces                                                                                                  |
| 9  | Studies on temperature distribution and heat transfer in HTST pasteurizer                                                                           |
| 10 | Design problems on heat exchangers – I                                                                                                              |
| 11 | Design problems on heat exchangers - II                                                                                                             |
| 12 | Design problems on heat exchangers - III                                                                                                            |
| 13 | Determination of viscosity of different food materials                                                                                              |
| 14 | Design problems on heat exchangers                                                                                                                  |
| 15 | Study of evaporators and their material and enthalpy balances                                                                                       |
| 16 | Study of evaporators and their material and enthalpy balances                                                                                       |

|    | <b>References</b>                                                                                                        |
|----|--------------------------------------------------------------------------------------------------------------------------|
| 1  | Cabe Mc., Smith J.C and Harriot P. <i>Unit operations of Chemical Engineering</i> . Mc Graw Hill Publishers. New Delhi.  |
| 2  | Mohesinin N. N. <i>Physical properties of Plant and Animal materials</i> .                                               |
| 3  | Stanley E.C. <i>Fundamentals of Food Engineering</i> . AVI Publishers. Westport. USA.                                    |
| 4  | Sahay K.M and Singh K.K. <i>Unit operations of Agricultural Processing</i> . Vikas Publishing House Pvt. Ltd. New Delhi. |
| 5  | Earle R.L. <i>Unit operations in Food Engineering</i> .                                                                  |
| 6  | Fellows P.J. <i>Food Processing Technology, Principles and Practice</i> . Wood Head Publishing Ltd., Cambridge, England. |
| 7  | HSE ( <i>Health and Safety Executive</i> ) information sheet no.24                                                       |
| 8  | Singh R. P and Heldman D.R. <i>Introduction to Food Engineering</i> . 3rd Edn.,                                          |
| 9  | Smith P.G. <i>Introduction to Food Process Engineering</i> .                                                             |
| 10 | Chakraverty A. <i>Post Harvest Technology of Cereals, Pulses and Oilseeds</i> .                                          |

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|----|--------------------------------------------------------------------------------------|
|    | Oxford & IBH Publishers. New Delhi.                                                  |
| 11 | Fennema. <i>Principles of Food Science</i> . Part II. Marcel Dekker Inc. publishers. |

## LECTURE NO. 1

INTRODUCTION TO MATERIAL HANDLING AND TRANSPORTATION-  
SELECTION OF MATERIAL HANDLING MACHINES AND CONVEYORS, BELT  
CONVEYOR; BELT CONVEYOR IDLERS, IDLER SPACING, BELT TENSION

### **Material handling Equipment**

**Material handling** includes a number of operations that can be executed either by hand (manual) or by mechanical means or devices **to convey material** and **to reduce the human drudgery**.

The most common types of mechanical devices for grain handling are;

1. Belt conveyor
2. Bucket elevator
3. Screw conveyor
4. Chain Conveyor
5. Pneumatic conveyor

### **Selection of material Handling machines and Conveyors**

The selection of proper conveying system is important for ease in operation and getting desired capacity for a particular product. Principles based on which the material handling equipment is selected:

- Based on the characteristics of the products being conveyed
- Working and climatic conditions.
- The capacity of conveying
- In a conveying system possibility of use of gravity.
- The capacity of handling / conveying equipment should match with the capacity of processing unit or units.
- Spillage of conveyed products should be avoided.
- Pollution of the environment due to noise or dust by the conveying system should also be avoided.

### **Belt conveyors**

A belt conveyor is an endless belt operating between two pulleys with its load supported on idlers. The belt may be flat for transporting bagged material or V-shaped. The belt conveyor consists of a belt, drive mechanism and end pulleys, idlers and loading and discharge devices (Fig. 1.1)



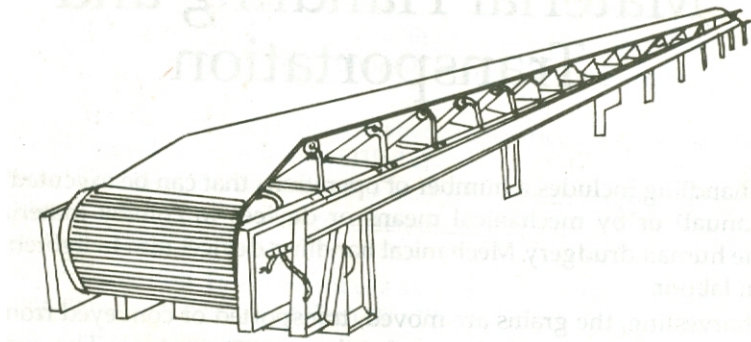


Fig.1.1 Diagram of a belt conveyor

On the belt conveyor baggage/ product lie still on the surface of belt and there is no relative motion between the product and belt. This results in generally no damage to material. Belt can be run at higher speeds, so, large carrying capacities are possible. Horizontally the material can be transported to longer distance. The initial cost of belt conveyor is **high for short distances**, but for longer distances the initial cost of belt conveying system is low.

The first step in the design of a belt conveyor with a specified conveying capacity is to determine the speed and width of the belt.

The belt speed should be selected to minimise product spillage or removal of fines due to velocity of the belt. For transportation of grains, the belt speed should not increase 3.5 m/s. Generally, for grain conveying, belt speed of 2.5 to 2.8 m/s is recommended. The selection of belt width will depend upon the capacity requirement, speed of operation, angle of inclination of belt conveyor, trough angle and depth. The capacity of belt conveyor can be calculated as:

$$\text{Capacity, m}^2/\text{h} = (\text{area of cross - section, m}^2) \times (\text{belt - speed, m/min}) \times 60$$

**Belt conveyor idlers:** The efficiency of belt conveyor is largely dependent on idlers. For higher efficiency of belt conveying systems, the idlers must be accurately made and provide a rigid framework. This will maintain a permanent, well balanced smooth running alignment.

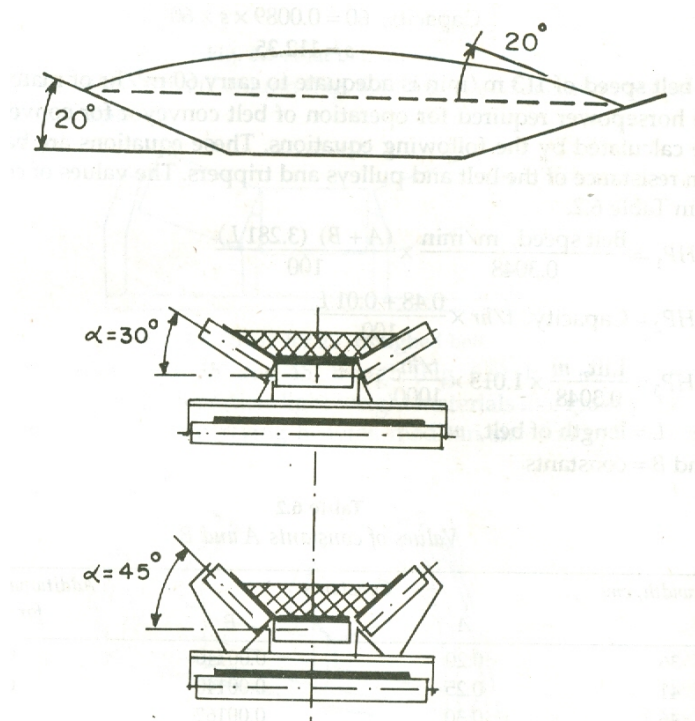


Fig.1.2 Various troughing configurations

There are three kinds of belt carrying idlers which are used in handling of bulk materials. The type of idlers affects the cross-sectional load on the belt.

1. The **flat belt idlers** are used for granular materials having an angle of repose of not less than  $35^\circ$ .
2. **Troughing idlers with  $20^\circ$  trough** is used for conveying all kinds of bulk materials.
3. **Troughing idlers with  $35^\circ$  and  $45^\circ$  trough angle** is mainly used for transportation of small particle light weight materials like grain, cotton seed etc. It is also used for carrying heavier, medium size lumps like crushed stones.

### Idler Spacing

The spacing between the idlers influences the retention of correct troughing. The incorrect idler spacing may result in belt undulation. The pitch of idlers is determined by the idler load rating or the carrying capacity of each idler, on the sag of the belt between the idlers, belt tension and belt speed. **As a token, the space between the successive idlers should be approximately equal to the width of belt.** *The spacing should not exceed 1.2 metres.*

### Belt tension

The tension developed at the drive pulley in transmitting the required power to move the loaded belt is known as effective tension. The effective tension is the sum of tension to move the empty belt, the tension to move the load horizontally and the tension to lift the material. The effective tension is related with the power required to move the belt and belt speed in the following manner.

$$\text{Effective Tension, } T_e = \frac{\text{Power in kW}}{\text{belt Speed, m/s}}$$

Grains are mostly discharged from the belt conveyor over the end pulley or at any other point along the conveyor by a scraper plough or a throw-off carriage known as a tripper.

While leaving the belt over the end pulley, product flow will describe the path of a parabola.

Belt conveyors can discharge grains at various locations by means of a movable tripper (Fig.1.3). Trippers are available as hand propelled, self propelled or automatic.

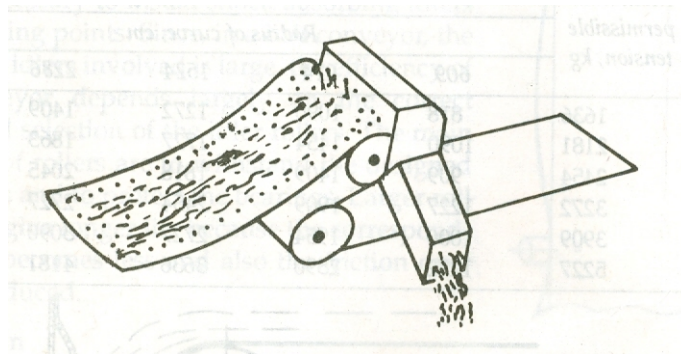


Fig.1.3 Tripper for discharge of materials

## LECTURE NO. 2

BUCKET ELEVATOR: HEAD SECTION, BOOT SECTION, ELEVATOR LEGS, ELEVATOR BELTS, BUCKETS, DRIVE MECHANISM, HP REQUIREMENT

### Bucket Elevator

A bucket elevator consists of buckets attached to a chain or belt that revolves around two pulleys one at top and the other at bottom. The vertical lift of the elevator may range between few metres to more than 50 m. **Capacities of bucket elevators may vary from 2 to 1000 t/hr.** Bucket elevators are broadly classified into two general types, (1) spaced bucket elevators and (2) continuous bucket elevators.

The spaced bucket elevators are further classified as,

- (1) centrifugal discharge elevators,
- (2) positive-discharge elevators,
- (3) marine leg elevators and
- (4) high-speed elevators.

The continuous bucket elevators are classified as

- (1) super capacity bucket elevators and
- (2) internal-discharge bucket elevators.

The spaced bucket centrifugal discharge type is most commonly used for elevating the grains. A centrifugal discharge bucket elevator is shown in Fig.2.1. The bucket elevator is a very efficient device for the vertical conveyance of bulk grains. Bucket elevators with belts are employed in food industries for vertical conveyance of grains, derivatives and flours. Bucket elevators are usually mounted at a fixed location, but they can also be mounted in a mobile frame. Bucket elevators have high capacities and it is a fairly cheap means of vertical conveyance.

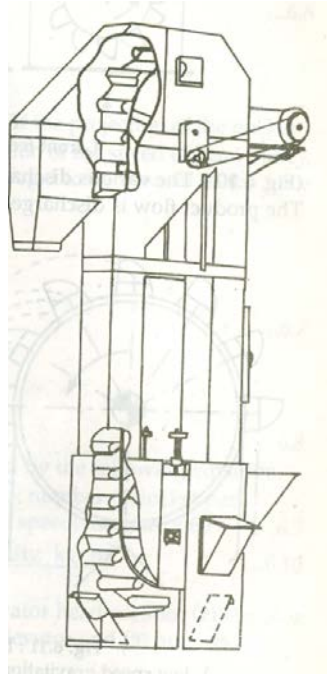


Fig.2.1 Bucket Elevator

It requires limited horizontal space and the operation of conveying is enclosed in housing, thus it is dust free and fairly quite. The bucket elevator has limited wear problem since the product is enclosed in buckets.

The buckets are enclosed in a single housing called leg, or two legs may be used. The return leg may be located at some distance from the elevator leg. The boot can be loaded from the front or back or both

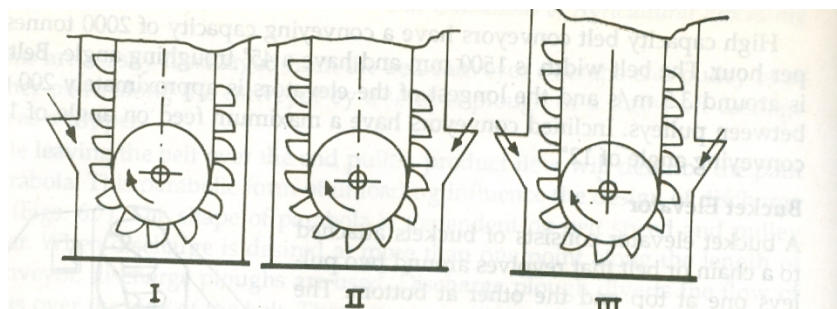


Fig.2.2 Bucket Feeding

The various discharge types of bucket elevators are shown in the following figure. The product flow is discharged either by means of gravity or centrifugal force.

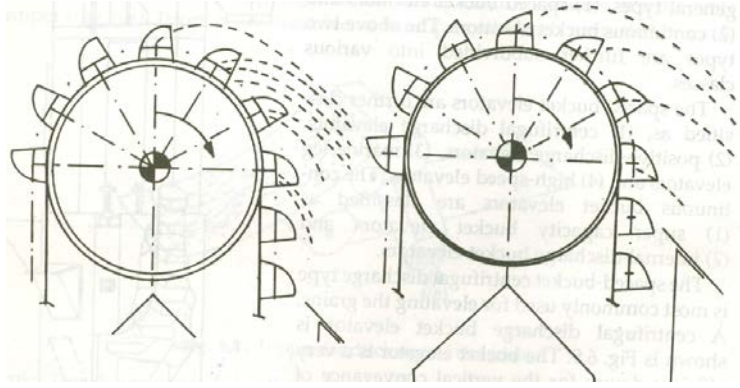


Fig.2.3 Bucket elevator's discharge methods

1. low speed gravitational discharge
2. high speed centrifugal discharge

The bucket elevator's capacity mainly depends on bucket size, conveying speed, bucket design and spacing, the way of loading and unloading, the bucket and the characteristic of bulk material. Belt speed is the first critical factor to consider. Bucket elevators with a belt carrier can be used at fairly high speeds of 2.5 to 4 m/ s.

The bucket elevator's capacity may be calculated by the following equation.

Elevator capacity,  $m^3/hr = \text{bucket capacity, } m^3 \times \text{No. of bucket per m of belt} \times \text{belt speed, m/min.} \times 60$

$$\text{Capacity, } t/h = \frac{\text{Capacity, } m^3/h \times \text{material density, } kg/m^3}{1000}$$

The main parts of a bucket elevator are,

- (1) elevator head section,
- (2) elevator boot section,
- (3) elevator legs,
- (4) belts for bucket elevator and
- (5) buckets.

### Head Section

A high speed conventional bucket elevator's head section is shown in Figure. The discharge side of the head should be shaped so that material thrown from the buckets may not deflect into the down leg. When the product is not thrown well clear of the buckets into the discharge chute, it will fall in the down leg. This is called as "back logging".

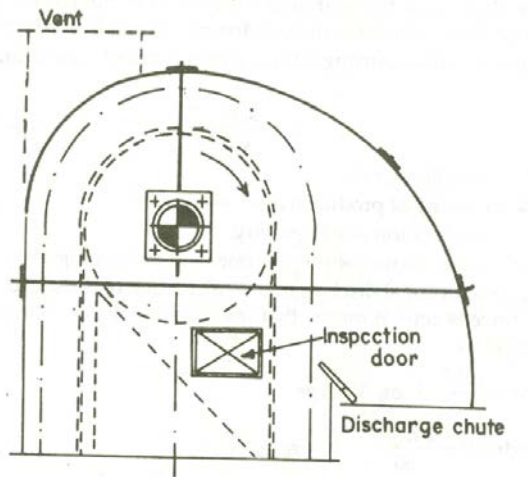


Fig.2.4 Diagram of bucket elevator head section

### Boot Section

Bucket elevator boots should be of bolted assembly to allow for proper maintenance and replacement of pulley, shaft and other accessories.

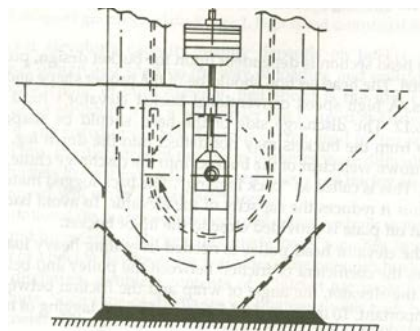


Fig.2.5 Bucket elevator boot section with automatic gravity take-up

### Elevator Legs

The up and down moving string of buckets in bucket elevators are enclosed in elevator legs. The elevator legs limit the emission of dust. These legs are constructed as all welded, bolted or riveted units. Cross section of different types of elevator legs is shown in the following Figure.

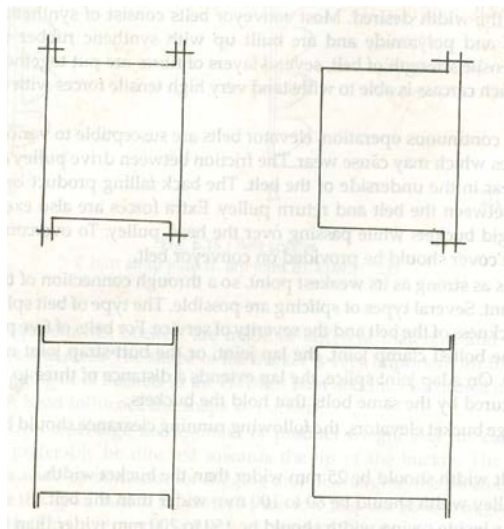


Figure. 2.6 Cross section of few types of elevator legs



## Elevator Belts

The bucket elevator belt has no support between the drive and the return pulleys, therefore, cross stiffness of belt is very important. The stretch limitation of the conveyor belts is also very important. The total stretch of the belt under maximum load should not exceed 1-2 % of the belt length.

A belt is as strong as its weakest point, so a through connection of the belt ends is important. Several types of splicing are possible. The type of belt splice depends on the thickness of the belt and the severity of service. For belts of five ply thickness or less, the bolted clamp joint, the lap joint, or the butt-strap joint may be used (Shown in Figure).

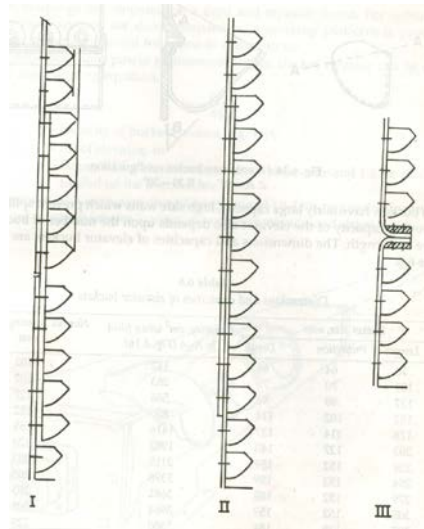


Fig.2.7 Belt Splices

I. butt strap joint II. Lap joint III. Clamp joint

## Buckets

As per the requirements, buckets are made of different materials and come in various shapes and sizes. The shape of the bucket is very important for filling and discharge. The common shape of bucket is shown in the following Figure. The top angle is generally taken as  $80^\circ$  while the bottom angle is between  $20-30^\circ$ .

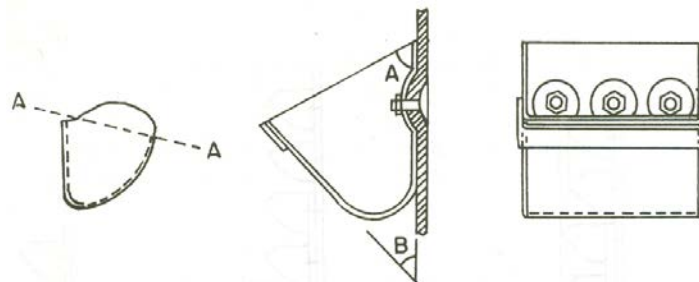


Fig.2.8 A common bucket configuration  
<  $80^\circ$  <B  $20-30^\circ$



**Drive mechanism**

The drive mechanism of a bucket elevator is located near the elevator head. At the elevator head, the belt is turned around the drive pulley. Drive motor with gear box and couplings are mounted on a rigid and separate frame.

**HP requirement**

The theoretical horsepower requirement for the bucket elevator can be calculated by the following equation.

$$hp = \frac{QHF}{4562}$$

where,

Q = capacity of bucket elevator, kg/min

H = lift of elevator, m

F = factor; 1.5 for elevators loaded on the up side and  
1.2 for elevators loaded on the bottom side

The theoretical horsepower should be increased 10-15% to provide for friction and power requirements for loading, power transmission and drive losses.

### LECTURE NO. 3

#### SCREW CONVEYOR: SCREW CONVEYOR DETAILS, VARIOUS SHAPES OF SCREW CONVEYOR TROUGH, CAPACITY AND HORSE POWER

##### Screw Conveyor

The screw conveyor consists of a tubular or U-shaped trough in which a shaft with spiral screw revolves. The screw shaft is supported hanger bearings at ends. The rotation of screw pushes the grain along the trough. A typical screw conveyor is shown in the following Figure. The screw conveyor is used in grain handling facilities, animal feed industries and other installations for conveying of products generally for short distances. Screw conveyor requires relatively high power and is more susceptible to wear than other types of conveyors. The pitch of a standard screw which is the distance from the centre of one thread to the centre of the next thread is equal to its diameter. For example a 10 cm diameter screw has a pitch of 10 cm.

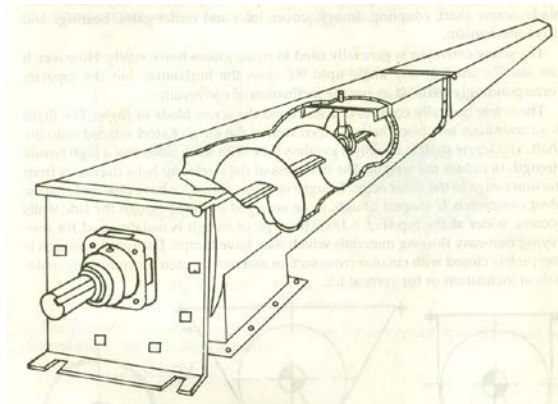


Fig.3.1 Screw conveyor

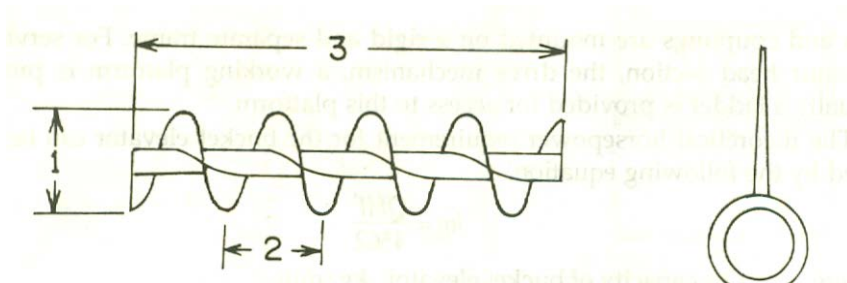


Fig. 3.2 Screw conveyor details

1. screw diameter
2. pitch of screw
3. screw length

As the screw conveyor's driving mechanism is simpler, and no tensioning device is required, the initial cost of the conveyor is lower than any other conveyor with the same length and capacity. The main parts of a screw

conveyor are, screw blade, screw shaft, coupling, trough, cover, inlet and outlet gates, bearings and drive mechanism.

The screw conveyor is generally used to move grains horizontally. However, it can also be used at any angle up to 90° from the horizontal, but the capacity correspondingly reduced as per the inclination of conveyance.

The screw basically consists of a shaft and the screw blade or flight. The flight is a continuous one piece helix shaped from a flat strip of steel welded onto the shaft. The screw shaft is usually a joint less tube with thick sides and a high tensile strength to reduce the weight. The thickness of the steel strip helix decreases from the inner edge to the outer edge. Troughs of screw conveyor have different shapes. Most common is U shaped trough. In an enlarged or flared trough the side walls become wider at the top (Figure). This type of trough is usually used for conveying non-easy flowing materials which may have lumps. The tubular trough is completely closed with circular cross-section and mostly used for conveying materials at inclination or for vertical lift.

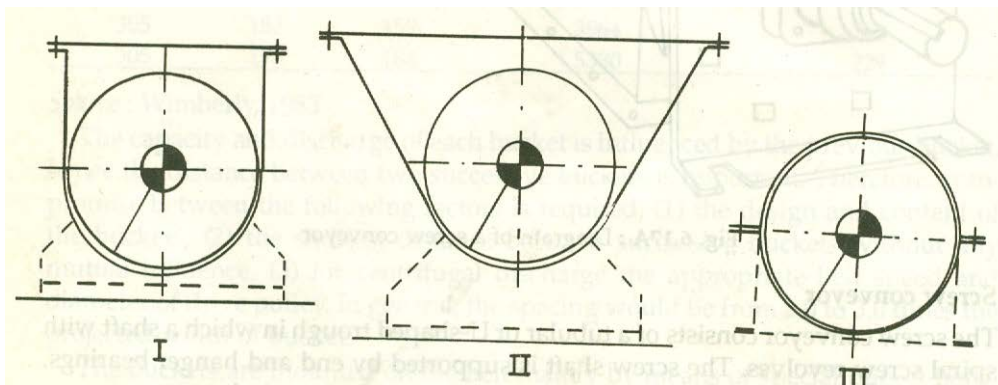


Fig.3.3 Various shapes of screw conveyor trough  
I. U-trough II. Flared trough III. tubular trough

If the screw conveyor is used to convey different materials, mixing of products is possible. The capacity of screw conveyor is influenced by the screw diameter, inclination of the screw blade, speed of the blade, shaft diameter and cross-section of loading. The theoretical conveyance capacity of the screw conveyor can be given by the following equation.

$$\text{Capacity } Q, m^3/hr = 47.2 (D^2 - d^2) \times P \times n$$

where,

D = screw diameter, m

d = shaft diameter, m

p = pitch, m

n = rpm

The theoretical capacity is more than the actual capacity because of screw housing clearance and the loading factor (Figure 3.4).

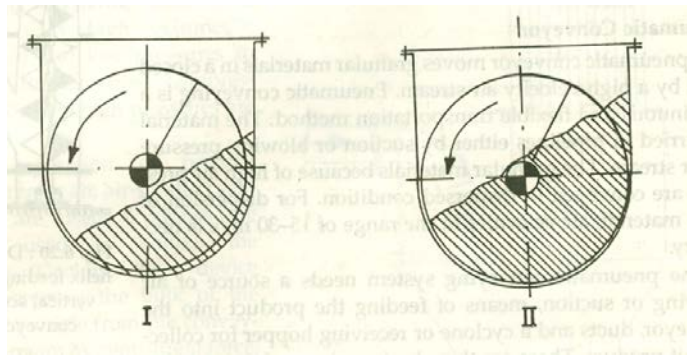


Fig.3.4 Screw conveyor loading factor  
I. 30% loading II. 55% loading

The power requirement of screw conveyors for horizontal operation is determined by the following equation.

$$\text{Horse power} = QLWF/4560$$

where,  $Q$  = conveyor capacity,  $\text{m}^3/\text{hr}$   
 $L$  = conveyor length, m  
 $W$  = bulk material weight,  $\text{kg}/\text{m}^3$   
 $F$  = material factor (for paddy 0.4)

If the calculated horsepower is less than 1.0, double the value.

horse power = 1 to 2 multiply the value by 1.5

horse power = 2 to 4 multiply the value by 1.25

horse power = 4 to 5 multiply the value by 1.1

For horsepower values of more than 5, no correction is required.

## LECTURE NO. 4

### PNEUMATIC CONVEYOR, LIMITATIONS OF PNEUMATIC CONVEYING, CHAIN CONVEYOR

#### Pneumatic Conveyor

The pneumatic conveyor moves granular materials in a closed duct by a **high velocity air stream**. Pneumatic conveying is a continuous and flexible transportation method. The material is carried in pipelines either by suction or blowing pressure of air stream. The granular materials because of high air pressure are conveyed in dispersed condition. For dispersion of bulk material, air velocities in the range of 15-30 m/s is necessary.

The pneumatic conveying system needs a source of air blowing or suction, means of feeding the product into the conveyor, ducts and a cyclone or receiving hopper for collection of product. There are three basic systems of pneumatic conveying. These are pressure or blowing system, suction or vacuum system, and combined push-pull or suck blow system.

In blowing or positive pressure systems, the product is conveyed by using air pressures greater than the atmospheric pressure.

The selection of air mover is the most important aspect of the design of a pneumatic conveying system. In design, the two factors, (1) supply air pressure and (2) the volumetric flow rate of air should be considered.

For separation of product particles from air, air-product separators are used. Cyclones are mostly used to collect the particles. Cyclone is a device which removes the bulk of the product particle from the conveying air stream by centrifugal force. In some cyclone, a fabric filter is attached to remove residual dust and fine product particles from the air stream (Figure 4.1).

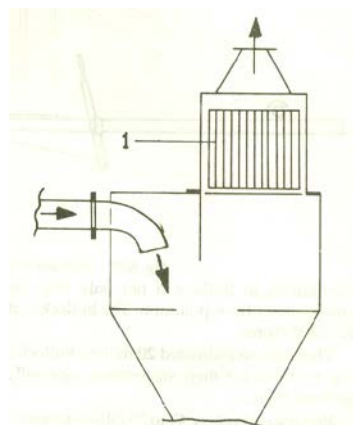


Fig. 4.1 Separation of product particles from air by means of a fabric filter

### **Limitations of Pneumatic Conveying**

1. Erosion of solid surfaces and equipment surfaces by solid particles with conveying air stream.
2. In case of bends or misaligned sections, the erosion problem becomes severe.
3. Chances of repeated impacts between the particles and the solid surfaces are high. Due to such impacts, product degradation results.

### **Chain Conveyor**

A chain is a reliable machine component, which transmits power by means of tensile forces, and is used primarily for power transmission and conveyance systems. The function and uses of chain are similar to a belt. Chains are divided into five types based on material of composition or method of construction.

Cast iron chain

Cast steel chain

Forged chain

Steel chain

Plastic chain

## LECTURE NO.5

### PRETREATMENT UNIT OPERATIONS: CLEANING, SORTING: FIXED APERTURE SORTING

#### **Pretreatment Unit Operations**

At the time of harvest or slaughter, most foods are likely to contain contaminants, to have components which are inedible or to have variable physical characteristics (for example shape, size or colour). It is therefore necessary to perform one or more of the unit operations of cleaning, sorting, grading or peeling to ensure that foods with a uniformly high quality are prepared for subsequent processing.

#### **Cleaning**

Cleaning is the unit operation in which contaminating materials are removed from the food and separated to leave the surface of the food in a suitable condition for further processing. A classification of the type of contaminants found on raw foods is shown in the following Table.

Table **Contaminants found on raw foods**

| Type of contaminant | Examples                                       |
|---------------------|------------------------------------------------|
| Metals              | Ferrous and non-ferrous metals, bolts, filings |
| Mineral             | Soil, engine oil, grease, stones               |
| Plant               | Leaves, twigs, weed seeds, pods and skins      |
| Animal              | Hair, bone, excreta, blood, insects, larvae    |
| Chemical            | Fertilizer, pesticides, herbicides             |
| Microbial cells     | Soft rots, fungal growth, yeasts               |
| Microbial products  | Colors, flavors, toxins                        |

Peeling fruits and vegetables, skinning meat or descaling fish are also considered as cleaning operations. In vegetable processing, blanching helps to clean the product. Cleaning should take place at the earliest opportunity in a food process both to prevent damage to subsequent processing equipment by stones, bone or metals, and to prevent time and money from being spent on processing contaminants which are then discarded. In addition, the early removal of small quantities of food contaminated by micro-organisms prevents the subsequent loss of the remaining bulk by microbial growth during storage or

delays before processing. Cleaning is thus an effective method of reducing food wastage, improving the economics of processing and protecting the consumer.

**Equipment for cleaning is categorized into** *wet procedures* (for example soaking, spraying, flotation washing and ultrasonic cleaning) and *dry procedures* (separation by air, magnetism or physical methods).

### **Wet cleaning**

Wet cleaning is more effective than dry methods for removing soil from root crops or dust and pesticide residues from soft fruits or vegetables. It is also dustless and causes less damage to foods than dry methods. Different combinations of detergents and sterilants at different temperatures allow flexibility in operation. However, the use of warm cleaning water may accelerate chemical and microbiological spoilage unless careful control is exercised over washing times and subsequent delays before processing.

Furthermore wet procedures produce large volumes of effluent, often with high concentrations of dissolved and suspended solids (measured as biological oxidation demand (BOD) or chemical oxidation demand (COD)). Examples of wet-cleaning equipment include spray washers, brush washers, drum or rod washers, ultrasonic cleaners and flotation tanks.

### **Dry cleaning**

Dry cleaning procedures are used for products that are smaller, have greater mechanical strength and possess lower moisture content (for example grains and nuts). After cleaning, the surfaces are dry, to aid preservation or further drying. Dry procedures generally involve smaller cheaper equipment than wet procedures do and produce a concentrated dry effluent which may be disposed of more cheaply

The main groups of equipment used for dry cleaning are:

- air classifiers
- magnetic separators
- separators based on screening of foods

### **Removing contaminants and foreign bodies**

Physical separation of contaminants from foods is possible when the food has a regular well-defined shape. For example round foods (peas, blackcurrants and rapeseed ) are separated from contaminants by exploiting their ability to roll



down an inclined, upward moving conveyor belt. A disc separator, used to separate grain from weed seeds, consists of a series of vertical metal discs with precisely engineered indentations in the sides that match the shape of the grain. Screens are also used to remove contaminants from foods.

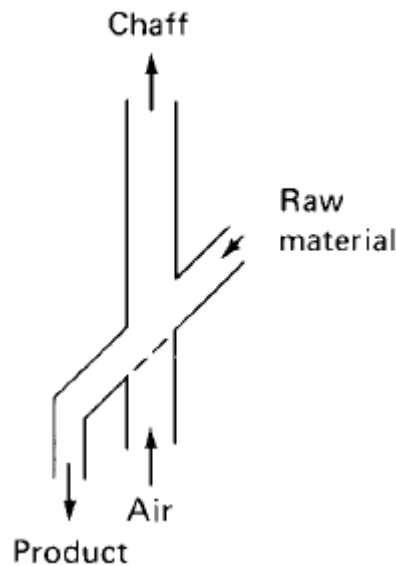


Fig. 5.1 Separation of chaff from grain by aspiration cleaning.

Contamination by metal fragments or bolts from machinery is a potential hazard in all processing. Raw materials may pass through metal detectors before processing and all packaged foods are checked for contamination. **Ferrous metals** are removed by either permanent magnets or electromagnets. Electromagnets are easier to clean (by switching off the power supply) but permanent magnets are cheaper.

### **Sorting**

Sorting is the separation of foods into categories on the basis of a measurable physical property. Like cleaning, sorting should be employed as early as possible to ensure a uniform product for subsequent processing. The four main physical properties used to sort foods are size, shape, weight and colour.

### **Shape and size sorting**

The particle size distribution of a material is expressed as either the mass fraction of material that is retained on each sieve or the cumulative percentage of material retained.

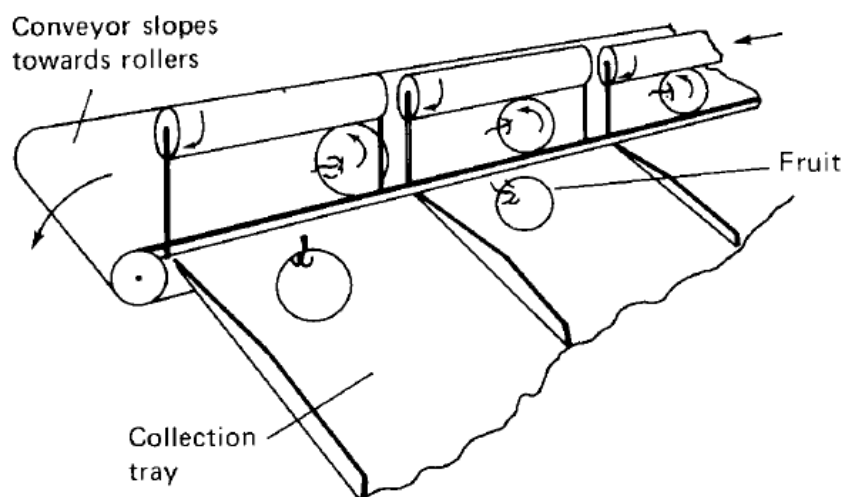


Fig. 5.2 Belt-and-roller sorter.

The shape of some foods is important in determining their suitability for processing or their retail value. For example, for economical peeling, potatoes should have a uniform oval or round shape without protuberances.

Shape sorting is accomplished either manually or mechanically.

**Size sorting** (termed *sieving* or *screening*) is the separation of solids into two or more fractions on the basis of differences in size. It is particularly important when the food is to be heated or cooled as the rate of heat transfer is in part determined by the size of the individual pieces and variation in size would cause over-processing or under-processing. Additionally, foods which have a uniform size are said to be preferred by consumers.

Screens with either **fixed or variable apertures** are used for size sorting. The screen may be stationary or, more commonly, rotating or vibrating.

#### **Fixed aperture screens**

Two common types of fixed aperture screen are the flat bed screen (or sieve) and the drum screen (rotary screen or reel). The multideck flat bed screen (Figure 5.3) has a number of inclined or horizontal mesh screens, which have aperture sizes from 20  $\mu\text{m}$  to 125 mm, stacked inside a vibrating frame. Food particles that are smaller than the screen apertures pass through under gravity until they reach a screen with an aperture size that retains them. The smallest particles that are separated commercially are of the order of 50  $\mu\text{m}$ .

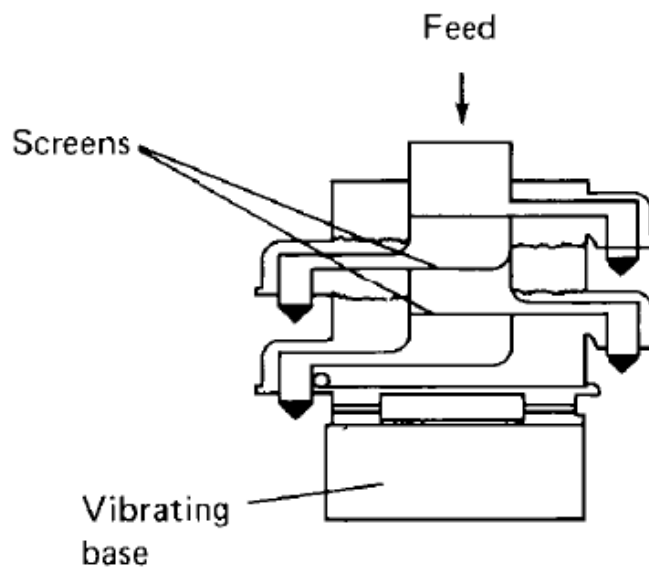


Fig.5.3 Multideck flat bed screen

The capacity of a screen is the amount of food that passes through per square metre per second.

The rate of separation is controlled by:

- the shape and size distribution of the particles
- the nature of the sieve material
- the amplitude and frequency of shaking
- the effectiveness of methods used to prevent blocking (or blinding) of the sieves.

These types of screens are widely used for sorting dry foods (for example flour, sugar and spices).

The main problems encountered are:

- excessive moisture or high humidity, which causes small particles to stick to the screen or to agglomerate and form larger particles, which are then discharged as oversize
- blinding, particularly if the particle size is close to that of the screen aperture
- high feed rates, which cause the screens to become overloaded and small particles, are discharged with the oversized particles.

Where vibration alone is insufficient to separate particles adequately, a gyratory movement is used to spread the food over the entire sieve area, and a vertical jolting action breaks up agglomerates and dislodges particles that block sieve apertures.

Many types of drum screen are used for sorting small-particulate foods (for example nuts, peas or beans) that have sufficient mechanical strength to withstand the tumbling action inside the screen. Drum screens are almost horizontal (5–10° inclination), perforated metal or mesh cylinders. They may be **concentric** (one inside another), **parallel** (foods leave one screen and enter the next (Figure 5.4)) or **series** (a single drum constructed from sections with different sized apertures). All types have a higher capacity than flat bed screens and problems associated with blinding are less severe than with flat bed screens. The capacity of drum screens increases with their speed of rotation up to a critical point. Above this the food is held against the screen by centrifugal force and results in poor separation. Similarly there is an increase in capacity with the angle of the screen up to a critical angle. Above this the residence time is too short and products pass through without separation.

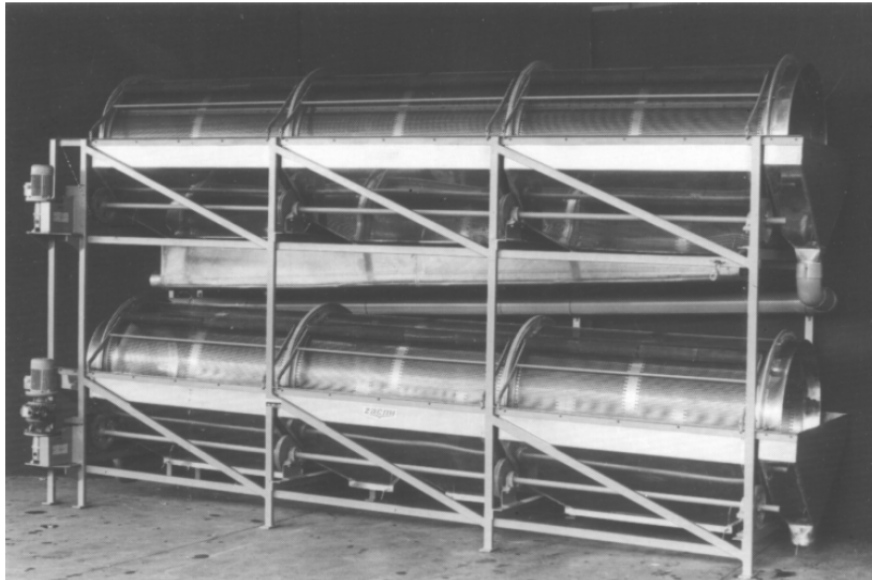


Fig. 5.4 Parallel drum screen.

## LECTURE NO. 6

SORTING: VARIABLE APERTURE SCREENS, IMAGE PROCESSING, COLOR SORTING, WEIGHT SORTING AND GRADING

### **Variable-aperture screens**

Variable-aperture screens have either a continuously diverging aperture or a stepwise increase in aperture. Both types handle foods more gently than drum screens and are therefore used to sort fruits and other foods that are easily damaged. Continuously variable screens employ pairs of diverging rollers, cables or felt-lined conveyor belts. These may be driven at different speeds to rotate the food and thus to align it, to present the smallest dimension to the aperture (Figure).



Figure 6.1 Sorting lemons on a roller sorter.

Stepwise increases in aperture are produced by adjusting the gap between driven rollers and an inclined conveyor belt (Refer Figure on belt and roller sorter). The food rotates and the same dimension is therefore used as the basis for sorting (for example the diameter along the core of a fruit).

### **Image processing**

*Image processing is used to sort foods on the basis of length, diameter, and number of surface defects and orientation of the food on a conveyor as well as colour. It has been used for example with maize cobs, which pass beneath*

three video cameras, placed 120° apart above a conveyor belt. The images of the surface of the cob are recorded and stored in the memory of a microprocessor. The information is then analyzed and compared with pre-programmed specifications for the product, and the cob is either rejected or moved into a group with similar characteristics.

### **Colour sorting**

Manual sorting by colour is still widely used but is increasingly expensive in both labour costs, operator training and the space required for sorting tables. There has therefore been considerable development of machine vision sorting systems which are said to have lower operating costs and greater accuracy than manual methods. These include monochrome (black and white), bichrome (4100 shades of red and green) and trichromatic or full colour (262 000 shades of red, green and blue, with optional infrared). Each is controlled by a programmable logic controller which has pre-set programs for different products that are easily changeable by operators using a video display. They are used for example, to sort potatoes for defects and blemishes by identifying dark areas on the potato surface. Light sensitive cells in the camera (termed 'pixels') *produce a voltage that is proportional to the intensity of light received. An electronic circuit that receives a lower voltage than the pre-set value can thus detect darker objects or areas which reflect less light than normal.* The voltage produced in the electronic circuit can be adjusted to alter the sensitivity of detection. Up to 10 tonnes of product per hour pass beneath the cameras on conveyors operating at 150–180 m per min. Defective items are removed by electronically controlled air jets that can operate for 20 milliseconds, thus covering 50 mm of the belt length in a single blast. In another system, vegetables in free-fall are scanned 1000 times per second, as they leave a conveyor belt, using concentrated helium-neon or laser light beams and a high-speed rotating mirror. The machine detects differences in reflectivity between good product and unwanted material.

Small-particulate foods may be automatically sorted at high rates using microprocessor controlled colour sorting equipment. Particles are fed into the chute one at a time. The angle, shape and lining material of the chute are altered to control the velocity of the pieces as they pass a photodetector. The colour of the background and the type and intensity of the light used for illuminating the food (including infrared and ultraviolet options) are closely controlled for each product. Photodetectors measure the reflected colour of each piece and

compare it with pre-set standards, and defective foods are separated by a short blast of compressed air. The computer can store 100 named product configurations to enable rapid changeover to different products using an operator touchpad.

Typical applications include peanuts, rice, diced carrot, maize kernels, cereals, snack foods and small fruits.

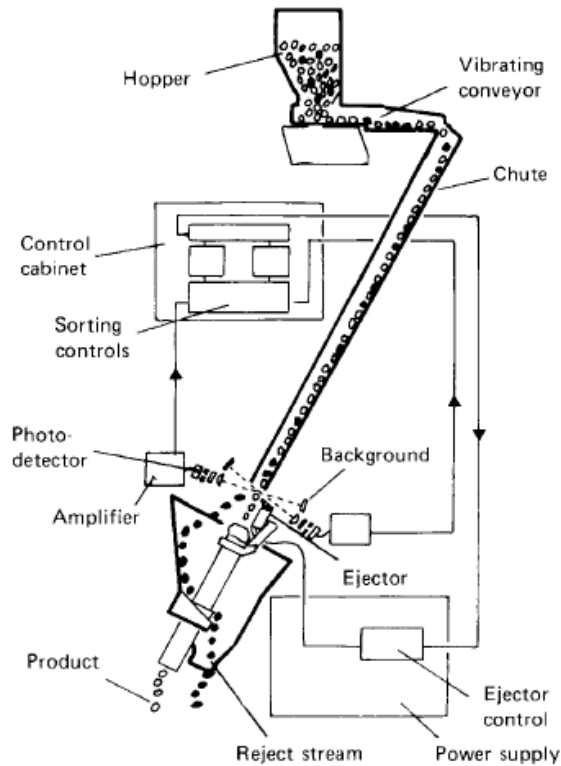


Fig. 6.2 Colour sorter.

A different type of equipment employs a sensor located above a conveyor belt, which views products as they pass beneath. The sensor detects up to eight colours and provides an alarm or control signal whenever a pre-selected colour passes the detector beam. It is also able to distinguish between different coloured foods which are to be processed separately. In a more sophisticated system, foods which have variations in colour over their surface are colour sorted by image processing. The foods are fed in rows on a roller conveyor beneath a video camera. The relative intensities of reflected red, green and yellow light are transmitted to the microcomputer which constructs a composite image of each piece of food, showing both the spread of colour and the mean colour of inspected foods. The computer compares the constructed image with pre-set specifications and activates a compressed air ejector or a mechanical

deflector to remove rejected food. When this type of system is used to sort baked goods, it is also used to control directly the gas or electricity supply to the ovens, which is reported to reduce energy consumption in ovens by 20%. The sorter can be easily adapted to different foods, by operators using the microprocessor keypad.

### **Weight sorting**

Weight sorting is more accurate than other methods and is therefore used for more valuable foods (for example eggs, cut meats and some tropical fruits). Eggs are sorted at up to 12 000 per hour into six to nine categories with a tolerance of 0.5 g. They are first graded by 'candling' and then pass to the weight sorter. This consists of a slatted conveyor which transports the eggs above a series of counterbalanced arms. The conveyor operates intermittently and while stationary, the arms raise and weigh the eggs. Heavy eggs are discharged into a padded chute and lighter eggs are replaced on the conveyor to travel to the next weigher.

**Aspiration** and **flotation** sorting use differences in density to sort foods and are similar in principle and operation to aspiration and flotation cleaning. Grains, nuts and pulses are sorted by aspiration. Peas and lima beans are sorted by flotation in brine (specific gravity, 1.1162–1.1362). The denser, starchy, over-mature pieces sink whereas the younger pieces float.



Fig. Egg sorter.

### **Grading**

This term is often used interchangeably with sorting but strictly means 'the assessment of overall quality of a food using a number of attributes'. Sorting (that is separation on the basis of one characteristic) may therefore be used as part of a grading operation but not vice versa. Grading is carried out by operators



who are trained to simultaneously assess a number of variables. For example, eggs are visually inspected over tungsten lights (termed 'candling') to assess up to twenty factors and remove those that are for example, fertilized or malformed and those that contain blood spots or rot. Meats, for example, are examined by inspectors for disease, fat distribution, bone to flesh ratio and carcass size and shape. Other graded foods include cheese and tea, which are assessed for flavour, aroma, colour, etc. Apples are graded with the assistance of coloured cards that show the required characteristics of different grades in terms of colour distribution across the fruit, surface blemishes and size and shape of the fruit.

In some cases the grade of food is determined from the results of laboratory analyses (for example wheat flour is assessed for protein content, dough extensibility, colour, moisture content and presence of insects). In general, grading is more expensive than sorting owing to the higher costs of skilled operators. However, many attributes that cannot be examined automatically can be simultaneously assessed, and this produces a more uniform high-quality product.

## LECTURE NO. 7

### PEELING, DEHULLING, DEHUSKING

#### **Peeling**

Peeling is used in the processing of many fruits and vegetables to remove unwanted or inedible material, and to improve the appearance of the final product. The main consideration is to minimise costs by removing as little of the underlying food as possible and reducing energy, labour and material costs to a minimum. The peeled surface should be clean and undamaged.

There are five main methods of peeling:

1. flash steam peeling
2. knife peeling
3. abrasion peeling
4. caustic peeling
5. flame peeling.

#### **1. Flash steam peeling**

Foods (for example root crops) are fed in batches into a pressure vessel which is rotated at 4 – 6 rpm. High-pressure steam ( $1500 \times 10^3$  Pa) is introduced and all food surfaces are exposed to the steam by the rotation of the vessel for a predetermined time, which differs according to the type of food. The high temperatures cause rapid heating of the surface layer (within 15–30 s) but the low thermal conductivity of the product prevents further heat penetration, and the product is not cooked. Texture and colour are therefore preserved. The pressure is then instantly released which causes steam to form under the skin, and the surface of the food 'flashes off'. Most of the peeled material is discharged with the steam, and water sprays are needed only to remove any remaining traces. This type of peeler is gaining in popularity owing to the lower water consumption, minimum product loss, good appearance of the peeled surfaces, a high throughput (up to 4500 kg/h) with automatic control of the peeling cycle, and the production of a more easily disposable concentrated waste.

#### **Knife peeling**

Stationary blades are pressed against the surface of rotating fruits or vegetables to remove the skin. Alternatively the blades may rotate against

stationary foods. This method is particularly suitable for citrus fruits where the skin is easily removed and there is little damage or loss of fruit.

### **Abrasion peeling**

Food is fed onto carborundum rollers or placed into a rotating bowl which is lined with carborundum. The abrasive surface removes the skin and it is washed away by a copious supply of water. The advantages of the method include low energy costs as the process operates at room temperature, low capital costs, no heat damage and a good surface appearance of the food. Irregular product surfaces (for example 'eyes' on potatoes) may mar the appearance of the peeled product and require hand finishing.

The limitations of the method are:

- a higher product loss than flash peeling (25% compared with 8–18% losses, for vegetables)
- the production of large volumes of dilute waste which are difficult and expensive to dispose of
- relatively low throughputs as all pieces of food need to contact the abrasive surfaces.

### **Caustic peeling**

A dilute solution of sodium hydroxide (named lye) is heated to 100–120°C. In the older method of lye peeling, food is passed through a bath of 1–2% lye which softens the skin and the skin is then removed by high-pressure water sprays. Product losses are of the order of 17%. Although once popular for root crops, this method causes changes in the colour of some products and incurs higher costs. It is now largely replaced by steam or flash peeling.

A development of lye peeling is named dry caustic peeling. Food is dipped in 10% sodium hydroxide and the softened skin is removed with rubber discs or rollers. This both reduces water consumption and product losses and gives a concentrated skin 'paste' which is more easily disposed of.

### **Flame peeling**

Developed for onions, this peeler consists of a conveyor belt which carries and rotates the food through a furnace heated to 1000 °C. The outer 'paper shell' and root hairs are burned off, and the charred skin is removed by high-pressure water sprays. Average product losses are 9%.

## **Dehulling and Dehusking**

Dehulling is the process of removing the hulls (or chaff) from beans and other seeds. This is done using a machine known as a huller. To prepare the seeds to have oils extracted from them, they are cleaned to remove any foreign objects. Next, the seeds have their hulls, or outer coverings, or husk, removed.

Brown rice is produced by removing the husk from the paddy rice. The husk is removed by friction as the paddy grains pass between two abrasive surfaces that are moving at different speeds. After dehusking, the husk is removed by suction and transported to a storage dump outside the mill. Husk accounts for 20% of the paddy weight and an efficient husker should remove 90% of the husk in a single pass.

Rice hulling and shelling are different processes. So far in both the condition the major aim is milling of paddy to get rice. Shelling of paddy is such a term where the operation of taking out husk from paddy is known while hulling or dehusking is that process where not only husk is separated but some part of grain embryo and bran is also separated.

## LECTURE NO.8

### MIXING: INTRODUCTION, AGITATION, AGITATED VESSELS, MIXING OF LIQUIDS

#### **Mixing**

Mixing is the dispersing of components, one throughout the other. The mixing of liquids, solids and gases is one of the commonest of all operations in the food processing industries. Of the possible combinations of these states, those of principal interest are liquid/liquid mixtures, solid/solid mixtures, and liquid/solid mixtures or pastes.

Reasons for mixing are:

- to bring about intimate contact between different species in order for a chemical reaction to occur ; and
- to provide a new property of the mixture which was not present in the original separate components. **An example is** a food mixture of a given component for nutritional purposes.

It should be clear from the foregoing that mixing is brought about by agitation.

There are three criteria by which the performance of a mixer should be assessed. These are:

1. the degree of mixedness achieved,
2. the time required to bring about mixing, and,
3. the power consumption required.

#### **Agitation**

The agitation of a liquid is defined as the *establishment of a particular flow pattern within the liquid, usually a circulatory motion within a container*. Mixing is brought about by agitation.

#### **Purposes of agitation**

Liquids are agitated for a number of purposes, depending on the objectives of the processing step. These purposes include:

1. Suspending solid particles.
2. Blending miscible liquids, for example, methyl alcohol and water.
3. Dispersing a gas through the liquid in the form of small bubbles.

4. Dispersing a second liquid, immiscible with the first, to form an emulsion or a suspension of fine drops.
5. Promoting heat transfer between the liquid and a coil or jacket.

### **AGITATED VESSELS**

Liquids are most often agitated in some kind of tank or vessel, usually cylindrical in form and with a vertical axis. The top of the vessel may be open to the air; more usually it is closed. The proportions of the tank vary widely, depending on the nature of the agitation problem. A standardized design such as that shown in the following figure however, is applicable in many situations. The tank bottom is rounded, not flat, to eliminate sharp corners or regions into which fluid currents would not penetrate. The liquid depth is approximately equal to the diameter of the tank. An impeller is mounted on an overhung shaft, that is, a shaft supported from above. The shaft is driven by a motor, sometimes directly connected to the shaft but more often connected to it through a speed reducing gearbox. Accessories such as inlet and outlet lines, coils, jackets, and wells for thermometers or other temperature-measuring devices are usually included.

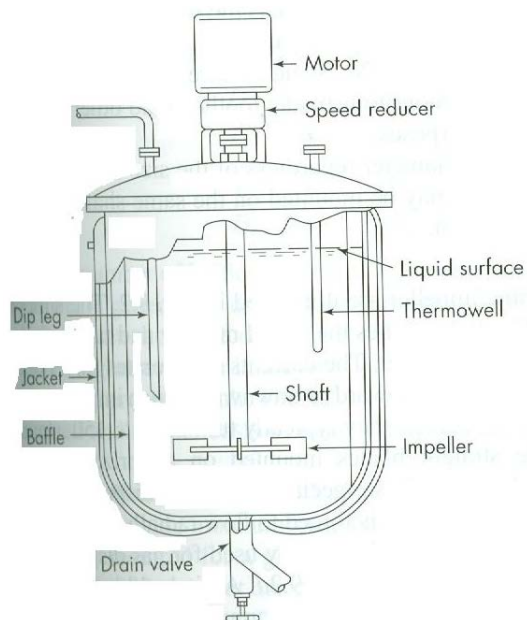


Figure 8.1 Typical Agitation Process Vessel

The impeller causes the liquid to circulate through the vessel and eventually return to the impeller. Baffles are often included to reduce tangential motion.

## **Mixing of Liquids - Liquid Mixing Equipment**

For the deliberate mixing of liquids, the propeller mixer is the most common and the most satisfactory. In using propeller mixers, it is important to avoid regular flow patterns such as an even swirl round a cylindrical tank, which may accomplish very little mixing. To break up these streamline patterns, baffles are often fitted, or the propeller may be mounted asymmetrically.

The mixing of liquids is achieved in an agitated tank. A large number of different types of impellers are in use; different impellers impart different flow patterns to the liquid and they must be matched to the rheology of the liquid and to the desired shear rate. Mixing vessels usually have rounded bottoms, rather than flat ones, to prevent the formation of dead spaces. The liquid depth is normally equal to the tank diameter. When an impeller rotates in a liquid the liquid is likely to swirl in a mass and a vortex will form (Figure). This is undesirable; the vortex may well draw air from the surface down to the impeller with the possibility either of unwanted dissolution of air or a waste of energy as the impeller rotates partly in air at the expense of agitating the liquid. Consequently baffles are fitted to the tank which consists of vertical strips of metal running the full depth of the inside surface of the tank. Normally four baffles are used, their width being about 10 % of the tank diameter. Baffles minimize vortex formation, prevent swirling of the liquid, and result in more rapid mixing.

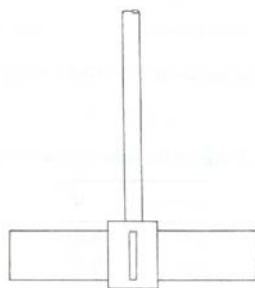


Figure 8.2 Paddle impeller

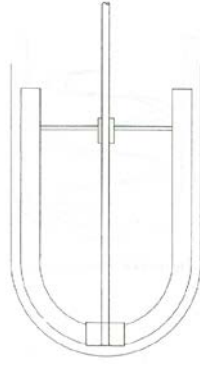


Figure 8.3 Anchor impeller

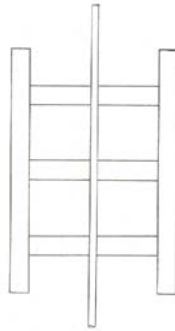


Figure 8.4 Gate Impeller

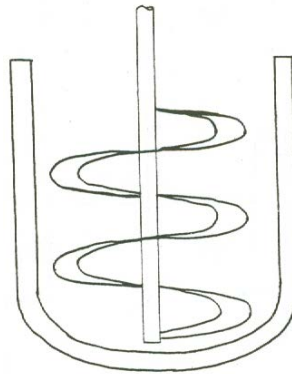


Figure 8.5 Helical Impeller

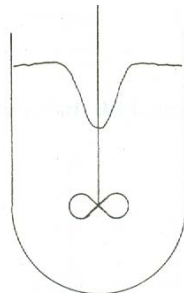


Figure 8.6 Vortex formation: without baffles



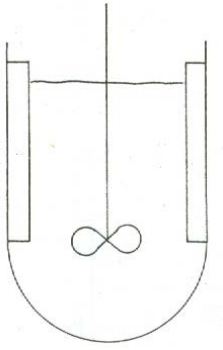


Figure 8.7 Vortex formation: with baffles

Various baffles can be used and the placing of these can make very considerable differences to the mixing performances. It is tempting to relate the amount of power consumed by a mixer to the amount of mixing produced, but there is no necessary connection and *very inefficient mixers can consume large amounts of power.*

## LECTURE NO.9

### MIXING OF SOLIDS: EQUIPMENT- RIBBON BLENDER, KNEADER, DOUBLE CONE MIXER, TUMBLING MIXERS, DOUGH AND PASTE MIXERS

#### Mixing of Solids

A theory for solids mixing, as is the case generally for the processing of particulate solids, is not available as it is for liquids. However a number of mixing mechanisms can be identified and to a limited extent these can be related to mixing equipment. The solids mixing mechanisms which can be identified are diffusion, convection, and shear.

Particles diffuse under the influence of a concentration gradient in the same way that molecules diffuse. They move by inter-particle percolation, that is, in the void spaces between other particles under the influence of either gravity or, in higher speed mixers, of centrifugal effects. Fick's law can be used to describe this phenomenon.

Convection describes the movement of groups of particles from one place to another within the mixer volume because of the direct action of an impeller or a moving device within the mixer body. As in convection within fluids this is likely to be a more significant effect than diffusion but diffusional effects will still be present.

The shear mechanism operates when slipping planes are formed within the particulate mass, perhaps because of the action of a blade, which in turn allow particles to exploit new void spaces through which particles can then diffuse.

In addition to these mixing mechanisms, segregation acts against mixing to separate components which have different physical properties. *Segregation is usually due to gravitational forces, but is heightened when centrifugal effects are present and occurs when particles have the possibility of falling through the spaces between other particles.* The degree of segregation is a function of particle size (with smaller particles being more likely to segregate), density, and shape. Thus, larger size differences and larger density differences in a particulate mixture are likely to bring about increased segregation and make

mixing more difficult. It is more difficult to quantify the effect of shape, although gross differences in shape are more likely to lead to poor mixing.

### **Equipment for Solids Mixing**

A huge variety of devices for the mixing of solids is available.

#### **Ribbon Blender**

The essential feature in these mixers is to displace parts of the mixture with respect to other parts. The ribbon blender, consists of a trough in which rotates a shaft with two open helical screws attached to it, one screw being right-handed and the other left-handed. As the shaft rotates sections of the powder move in opposite directions and so particles are vigorously displaced relative to each other.

It is usually operated in batch mode with mixer volumes up to about 15 m, but continuous operation is possible with feed rates up to 10 t/h. Helical ribbon mixers can be used for slightly cohesive solids, for very thin pastes or for the addition of liquids to solids. Mixing is strongly convective and segregation is far less pronounced than in either tumbling mixers or fluidised beds.

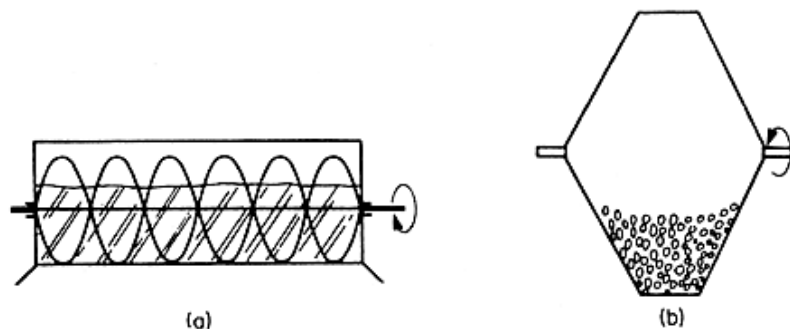


Figure 9.1 Mixers (a) ribbon blender, (b) double-cone mixer

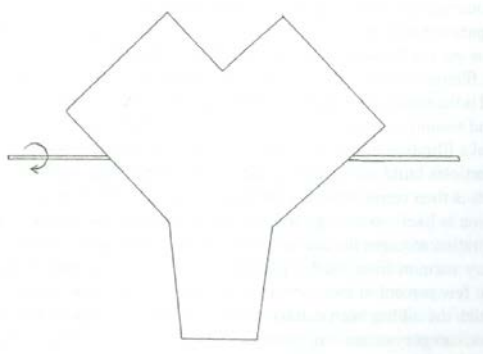


Figure 9.2 Y-cone mixer

**Tumbling mixers / Cone Mixers:** Essentially these are enclosed containers which rotate about a horizontal axis and include the horizontal drum, double-cone, V-cone, Y-cone, and cube. The above figures show double-cone mixer and Y-cone mixer. These mixers are operated in batch mode being partially filled with solids (up to about 60% by volume). Tumbling mixers are run at a fraction of the critical speed required for centrifugation (at which all the solids would be thrown outwards towards the mixer walls) with a practical maximum speed of about 100 rpm. They are used for free-flowing solids, but small amounts of liquid may be added, and are best suited for particles of similar size and density because strong segregation can occur. Such mixers may have baffles fitted to the inner walls which help to lift solids or alternatively may be fitted with ploughs to assist convection.

### **Dough and Paste Mixers**

Dough and pastes are mixed in machines that have, of necessity, to be heavy and powerful. Because of the large power requirements, it is particularly desirable that these machines mix with reasonable efficiency, as the power is dissipated in the form of heat, which may cause substantial heating of the product. Such machines may require jacketing of the mixer to remove as much heat as possible with cooling water.

Perhaps the most commonly used mixer for these very heavy materials is the kneader which employs two contra-rotating arms of special shape, which fold and shear the material across a cusp, or division, in the bottom of the mixer. The arms are of so-called sigmoid shape as indicated in below Figure 9.3.

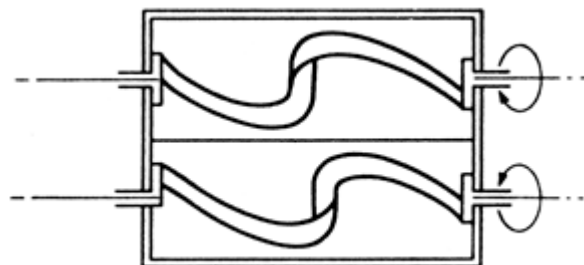


Figure 9.3 Kneader

They rotate at differential speeds, often in the ratio of nearly 3:2. Developments of this machine include types with multiple sigmoid blades along

extended troughs, in which the blades are given a forward twist and the material makes its way continuously through the machine.

Another type of machine employs very heavy contra-rotating paddles, whilst a modern continuous mixer consists of an interrupted screw which oscillates with both rotary and reciprocating motion between pegs in an enclosing cylinder. The important principle in these machines is that the material has to be divided and folded and also displaced, so that fresh surfaces recombine as often as possible.

## LECTURE NO.10

### FORMING-BREAD MOULDERS, PIE AND BISCUIT FORMERS, CONFECTIONERY MOULDERS

#### **Forming**

Forming is a **size enlargement operation** in which foods that have a high viscosity or a dough-like texture are moulded into a variety of shapes and sizes, often immediately after a mixing operation. It is used as a processing aid to increase the variety and convenience of baked goods, confectionery and snack foods. It has no direct effect on the shelf life or nutritional value of foods. Close control over the size of formed pieces is critical (*for example to ensure uniform rates of heat transfer to the centre of baked foods, to control the weight pieces of food, and to ensure the uniformity of smaller foods and hence to control fill weights*). Extrusion also has a forming function.

In high-viscosity liquids, pastes or doughs, a different action is needed. Here, mixing occurs by:

- *kneading* the material against the vessel wall or into other material
- *folding* unmixed food into the mixed part
- *shearing* to stretch the material.

Efficient mixing is achieved by creating and recombining fresh surfaces in the food as often as possible. However, because the material does not easily flow, it is necessary either to move the mixer blades throughout the vessel or to move the food to the mixer blades.

#### **Forming – Equipment**

There are many designs of moulding and forming equipment made specifically for individual products. In this section the equipment used for bread, biscuits, pies, snack foods and confectionery is described.

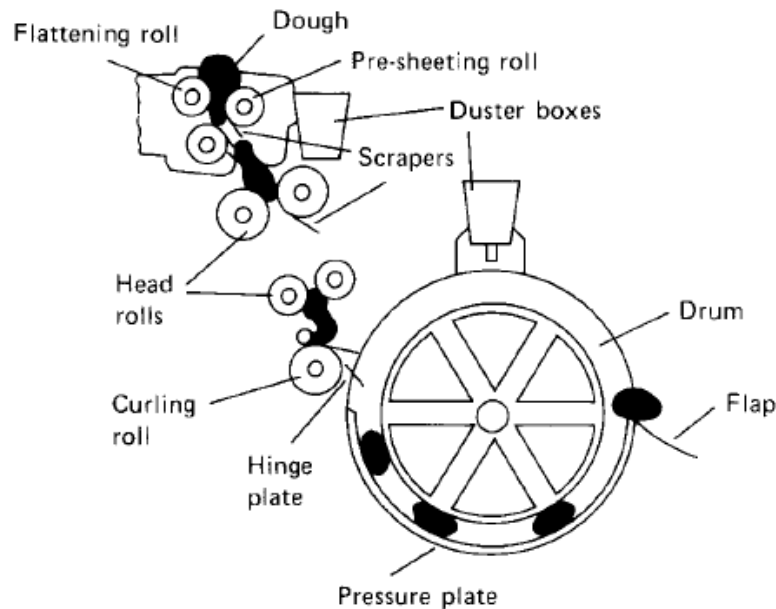


Figure 10.1 Drum moulder for bread doughs.

### Bread moulders

This equipment (Figure 10.1) shapes the dough into cylinders that will expand to the required loaf shape when proofed. The three stages are

1. Sheeting
2. Curling
3. rolling-sealing.

The first three sets of rollers have successively smaller gaps (or 'nips') to roll the dough gently into sheets without tearing. The sheet is loosely curled, rolled into a cylinder and then sealed by a revolving drum, which presses the dough against a pressure plate. The pressure is gradually increased to expel trapped air. Compression of the dough structure causes the moisture content of the sheet to increase at the trailing end. It is preferable to have the moist part of the dough at the centre of the cylinder, and a variety of designs are used to change the direction of the sheet to roll the trailing edge first (for example *cross-grain* moulders and *reverse sheeting* moulders).

### ENCASING

In forming and encasing balls of dough with other materials, the inner material and outer material are co-extruded and then divided and shaped by two 'encrusting discs' (Fig. 10.2 (a)). In contrast to conventional forming techniques, where the size of the product is determined by the size of the feed material, the relative thickness of the outer layer and the diameter of the inner sphere are determined by the flow rate of each material. It is therefore possible to alter the

relative thickness of inner and outer layers (Fig. 10.2(b)) simply by adjusting the flow rates, giving a high degree of flexibility for the production of different products. This equipment was developed in Japan for production of cakes having an outer layer of rice dough and filled with bean paste, but they have found wide application and are used to produce sweetbreads filled with jam, doughnuts, meat pies, hamburgers filled with cheese and fish filled with vegetables.

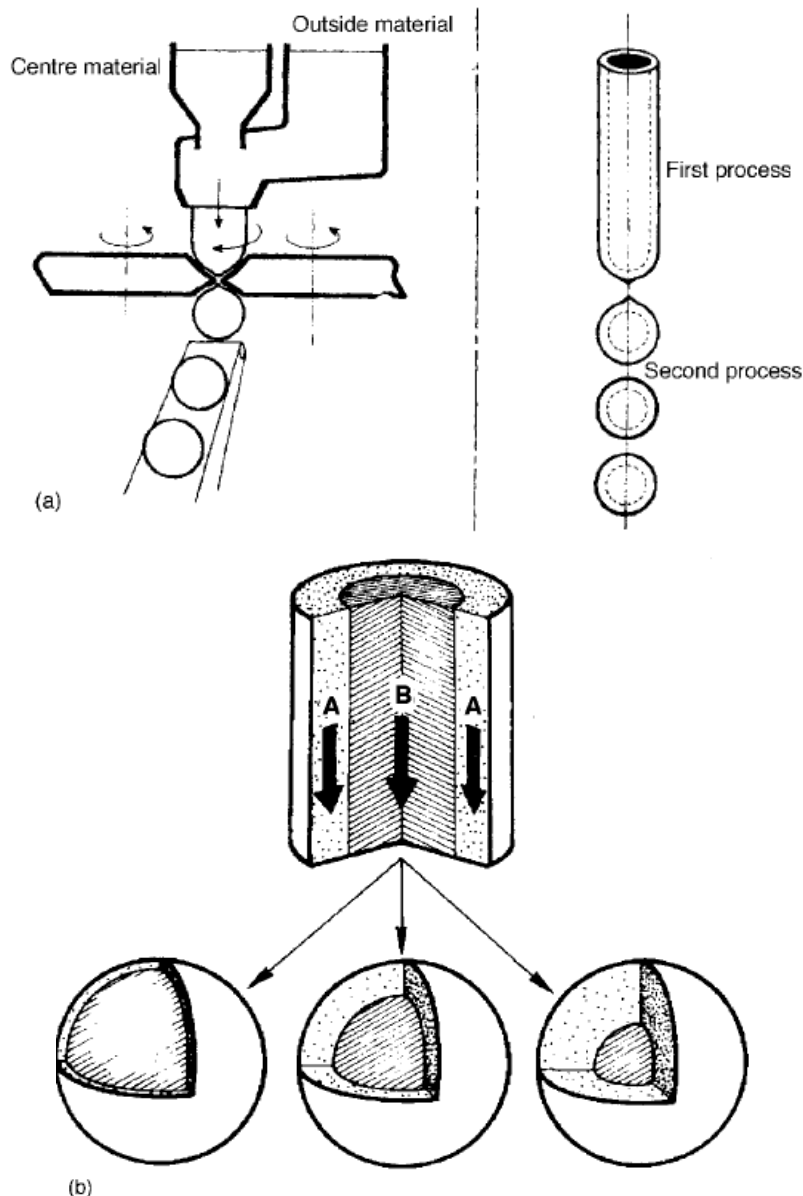


Figure 10.2 (a) Two revolving encrusting discs continuously divide food and shape it into balls; (b) differences in thickness of outer layer (A) and inner layer (B) result from different material flow rates.

### **Pie and biscuit formers**

Pie casings are formed by depositing a piece of dough into aluminium foil containers or re-usable pie moulds and pressing it with a die. A filling is then



deposited into the casing and a continuous sheet of dough is laid over the top. Finally the lids are cut by reciprocating blades (Figure 10.3).

Biscuits are formed by one of four methods:

1. the dough is pressed into shaped cavities in a *metal moulding roller* (die forming) (Figure 10.4(a))
2. shapes are cut from a sheet of dough using a *cutting roller*. Raised characters on a *printing roller* simultaneously imprint a design on the upper surface of the biscuit (Fig10.4 (b))
3. soft dough is extruded through a series of dies in a *wire-cut machine* (Fig. 10.4(c))
4. a continuous ribbon of dough is extruded from a *roul press* (similar to a wire cut machine but without the cutting wires), and the ribbon is then cut to the required length using a reciprocating blade.

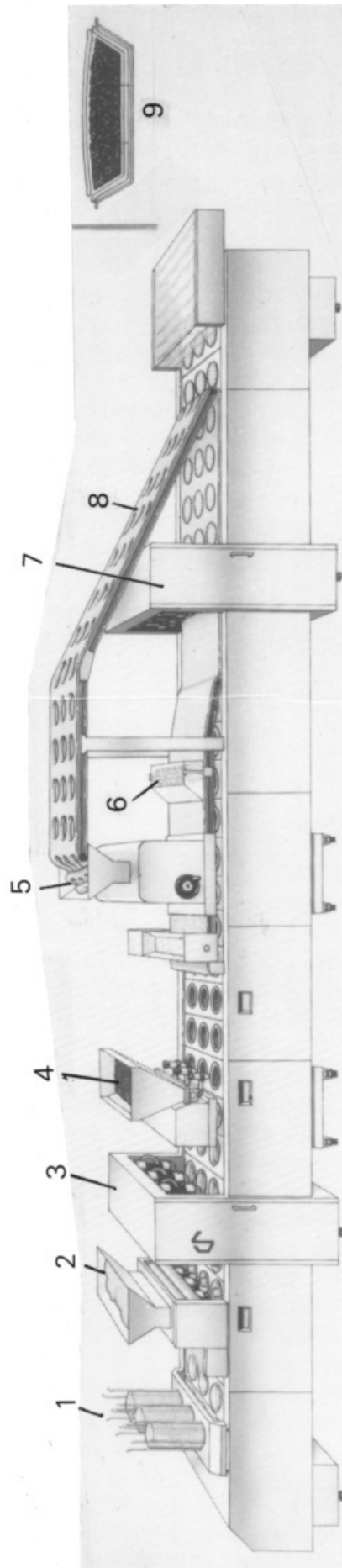


Figure 10.3 Pie manufacture: 1, foil dishes; 2, dough divider; 3, blocking unit; 4, filling depositor; 5, pastry lid sheeting machine; 6, rotary lattice cutter; 7, crimping/lidding unit; 8, scrap return conveyor; 9, pie cross section.

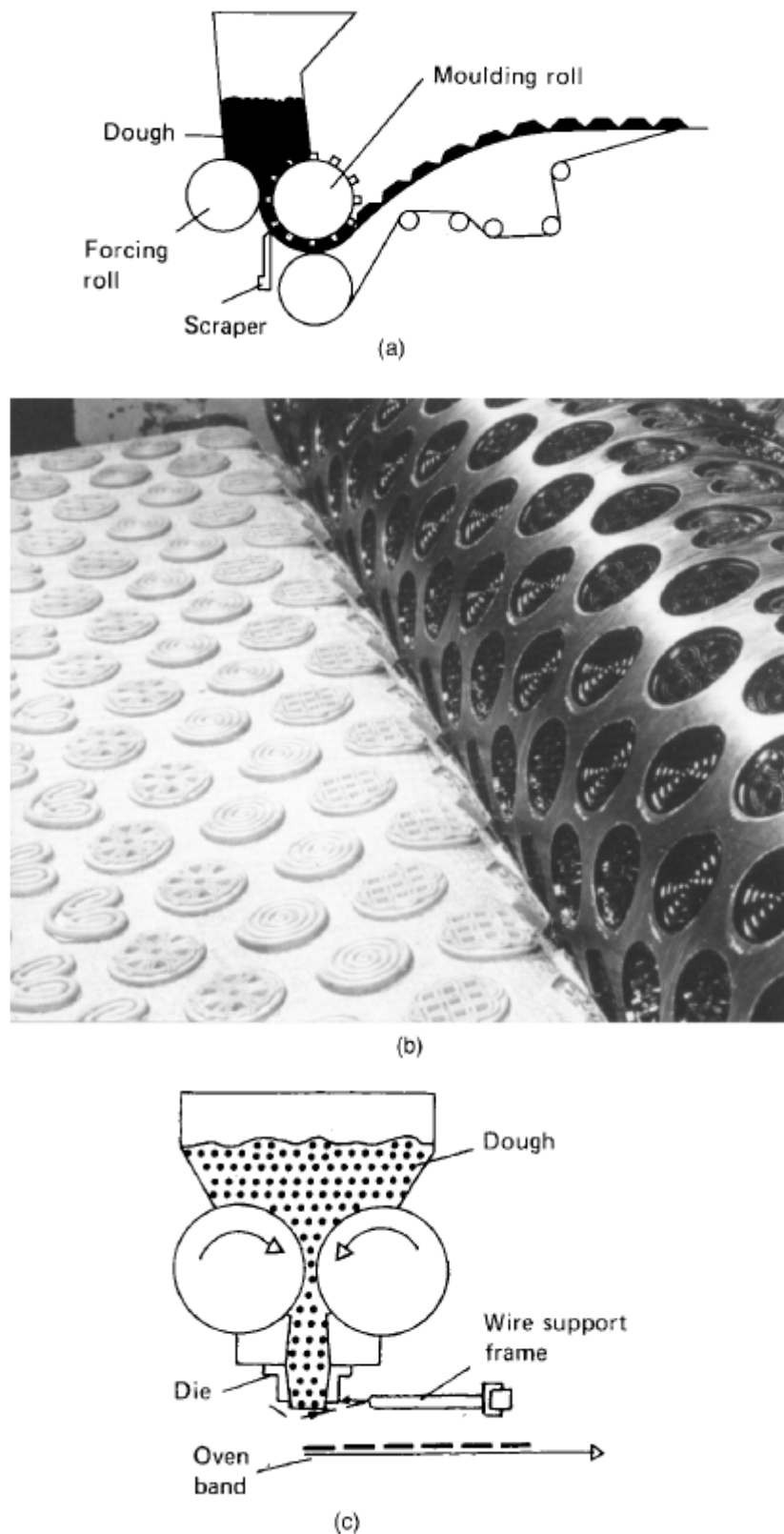


Figure 10.4 Biscuit formers: (a) rotary moulder; (b) moulding rollers; (c) wire-cut machine.

## Confectionery moulders

Confectionery depositing-moulding equipment consists of individual moulds, which have the required size and shape for a specific product, attached to a continuous conveyor. They are carried below a depositor, which has a piston filler to deposit accurately the required volume of hot sugar mass into each mould. Depositors can place food of a single type, in layers, or centre filled (Figure 10.5(a)) (for example liquid centres or chocolate paste around hard-boiled sweets). The food is then cooled in a cooling tunnel. When it has hardened sufficiently, individual sweets are ejected and the moulds restart the cycle (Figure 10.5(b)).

The three main types of equipment differ in the method of ejection, and the material used for the mould:

1. metal moulds fitted with ejector pins are used for hard confectionery (for example butterscotch)
2. flexible polyvinyl chloride moulds, which eject the food by mechanical deformation, are used for soft confectionery (for example toffee, fudge, jellies, caramel, fondant and chocolate)
3. polytetra fluoro ethylene-coated aluminium moulds, with compressed-air ejection, are used for jellies, gums, fondant and cremes.

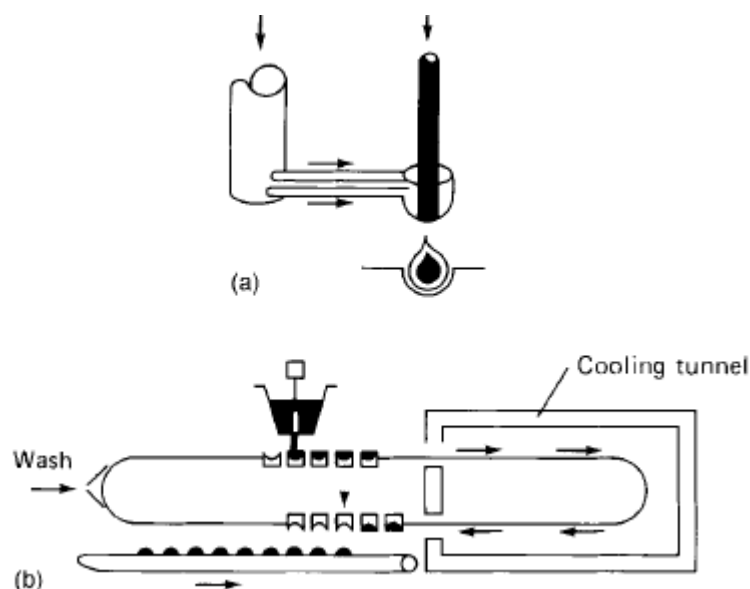


Figure 10.5 (a) Depositing centre-filled confectionery; (b) confectionery moulding: an air demoulding depositor.

## LECTURE NO. 11

SIZE REDUCTION: INTRODUCTION, GRINDING AND CUTTING, ENERGY USED IN GRINDING, KICK'S LAW, RITTINGER'S LAW, BOND'S LAW

### Size Reduction

Raw materials often occur in sizes that are too large to be used and, therefore, they must be reduced in size. Size reduction or 'comminution' is the unit operation in which the average size of solid pieces of food is reduced by the application of grinding, compression or impact forces. When applied to the reduction in size of globules of immiscible liquids (for example oil globules in water) size reduction is more frequently referred to as homogenization or emulsification. The size reduction of liquids to droplets is done by atomization. Size enlargement is achieved by extrusion, agglomeration or forming.

Size reduction has the following benefits in food processing:

- There is an increase in the surface-area-to-volume ratio of the food which increases the rate of drying, heating or cooling and improves the efficiency and rate of extraction of liquid components (for example fruit juice or cooking oil extraction).
- A similar range of particle sizes allows more complete mixing of ingredients (for example dried soup and cake mixes).

Size reduction and emulsification have little or no preservative effect. They are used to improve the eating quality or suitability of foods for further processing and to increase the range of products available. In some foods size reduction may promote degradation by the release of naturally occurring enzymes from damaged tissues, or by microbial activity and oxidation at the increased area of exposed surfaces, unless other preservative treatments are employed.

Different methods of size reduction are classified according to the size range of particles produced:

1. *Chopping, cutting, slicing and dicing:*

- (a) Large to medium
- (b) medium to small
- (c) small to granular

2. *Milling to powders or pastes of increasing fineness*

3. *Emulsification and homogenisation*

## GRINDING AND CUTTING

**Grinding and cutting** reduce the size of solid materials by mechanical action, dividing them into smaller particles. Perhaps the most extensive application of grinding in the food industry is in the milling of grains to make flour, but it is used in many other processes, such as in the grinding of corn for manufacture of corn starch, the grinding of sugar and the milling of dried foods, such as vegetables.

**Cutting** is used to break down large pieces of food into smaller pieces suitable for further processing, such as in the preparation of meat for retail sales and in the preparation of processed meats and processed vegetables.

In the grinding process, materials are reduced in size by fracturing them. The mechanism of fracture is not fully understood, but in the process, the material is stressed by the action of mechanical moving parts in the grinding machine and initially the stress is absorbed internally by the material as strain energy. When the local strain energy exceeds a critical level, which is a function of the material, fracture occurs along lines of weakness and the stored energy is released. Some of the energy is taken up in the creation of new surface, but the greater part of it is dissipated as heat. Time also plays a part in the fracturing process and it appears that material will fracture at lower stress concentrations if these can be maintained for longer periods. Grinding is, therefore, achieved by mechanical stress followed by rupture and the energy required depends upon the hardness of the material and also upon the tendency of the material to crack - its friability.

The force applied may be compression, impact, or shear, and both the magnitude of the force and the time of application affect the extent of grinding achieved. For efficient grinding, the energy applied to the material should exceed, by as small a margin as possible, the minimum energy needed to rupture the material. Excess energy is lost as heat and this loss should be kept as low as practicable.

The important factors to be studied in the grinding process are the amount of energy used and the amount of new surface formed by grinding.

## **Energy Used in Grinding**

Grinding is a very inefficient process and it is important to use energy as efficiently as possible. Unfortunately, it is not easy to calculate the minimum energy required for a given reduction process, but some theories have been advanced which are useful.

These theories depend upon the basic assumption that the energy required to produce a change  $dL$  in a particle of a typical size dimension  $L$  is a simple power function of  $L$ :

$$\frac{dE}{dL} = KL^n \quad (11.1)$$

where  $dE$  is the differential energy required,  $dL$  is the change in a typical dimension,  $L$  is the magnitude of a typical length dimension and  $K$ ,  $n$ , are constants.

**Kick** assumed that the energy required to reduce a material in size was directly proportional to the size reduction ratio  $dL/L$ . This implies that  $n$  in eqn. (11.1) is equal to -1. If  $K = K_K f_c$

where  $K_K$  is called Kick's constant and  $f_c$  is called the crushing strength of the material, we have:

$$dE/dL = K_K f_c L^{-1}$$

which, on integration gives:

$$E = K_K f_c \log_e(L_1/L_2) \quad (11.2)$$

Equation (2) is a statement of Kick's Law. It implies that the specific energy required to crush a material, for example from 10 cm down to 5 cm, is the same as the energy required to crush the same material from 5 mm to 2.5 mm.

**Rittinger**, on the other hand, assumed that the energy required for size reduction is directly proportional, not to the change in length dimensions, but to the change in surface area. This leads to a value of -2 for  $n$  in eqn. (1) as area is proportional to length squared. If we put:

$$K = K_R f_c$$

and so

$$dE/dL = K_R f_c L^{-2}$$

where  $K_R$  is called Rittinger's constant, and integrate the resulting form of eqn. (11.1), we obtain:

$$E = K_R f_c (1/L_2 - 1/L_1) \quad (11.3)$$

Equation (11.3) is known as Rittinger's Law. As the specific surface of a particle, the surface area per unit mass, is proportional to  $1/L$ , eqn. (11.3) postulates that the energy required to reduce  $L$  for a mass of particles from 10 cm to 5 cm would be the same as that required to reduce, for example, the same mass of 5 mm particles down to 4.7 mm. This is a very much smaller reduction, in terms of energy per unit mass for the smaller particles, than that predicted by Kick's Law.

It has been found, experimentally, that for the grinding of coarse particles in which the increase in surface area per unit mass is relatively small, Kick's Law is a reasonable approximation. For the size reduction of fine powders, on the other hand, in which large areas of new surface are being created, Rittinger's Law fits the experimental data better.

**Bond** has suggested an intermediate course, in which he postulates that  $n$  is  $-3/2$  and this leads to:

$$E = E_i (100/L_2)^{1/2} [1 - (1/q^{1/2})] \quad (11.4)$$

Bond defines the quantity  $E_i$  by this equation:  $L$  is measured in microns in eqn. (11.4) and so  $E_i$  is the amount of energy required to reduce unit mass of the material from an infinitely large particle size down to a particle size of 100 mm. It is expressed in terms of  $q$ , the reduction ratio where  $q = L_1/L_2$ .

Note that all of these equations [eqns. (11.2), (11.3), and (11.4)] are dimensional equations and so if quoted values are to be used for the various constants, the dimensions must be expressed in appropriate units. In Bond's



equation, if  $L$  is expressed in microns, this defines  $E_i$  and Bond calls this the Work Index.

The greatest use of these equations is in making comparisons between power requirements for various degrees of reduction.

### EXAMPLE 1. Grinding of sugar

Sugar is ground from crystals of which it is acceptable that 80% pass a 500  $\mu\text{m}$  sieve (US Standard Sieve No.35), down to a size in which it is acceptable that 80% passes a 88  $\mu\text{m}$  (No.170) sieve, and a 5-horsepower motor is found just sufficient for the required throughput. If the requirements are changed such that the grinding is only down to 80% through a 125  $\mu\text{m}$  (No.120) sieve but the throughput is to be increased by 50% would the existing motor have sufficient power to operate the grinder? Assume Bond's equation.

Solution:

Using the subscripts 1 for the first condition and 2 for the second, and letting  $m \text{ kg h}^{-1}$  be the initial throughput, then if  $x$  is the required power  
Now  $88 \mu\text{m} = 8.8 \times 10^{-6} \text{ m}$ ,  $125 \mu\text{m} = 125 \times 10^{-6} \text{ m}$ ,  $500 \mu\text{m} = 500 \times 10^{-6} \text{ m}$

$$E_1 = 5/m = E_i(100/88 \times 10^{-6})^{1/2} [1 - (88/500)^{1/2}]$$

$$E_2 = x/1.5m = E_i(100/125 \times 10^{-6})^{1/2} [1 - (125/500)^{1/2}]$$

$$E_2/E_1 = x/(1.5 \times 5) = \frac{(88 \times 10^{-6})^{1/2} [1 - (125/500)^{1/2}]}{(125 \times 10^{-6})^{1/2} [1 - (88/500)^{1/2}]}$$

$$\begin{aligned} x/(7.5) &= 0.84 \times (0.500/0.58) \\ &= 0.72 \end{aligned}$$

$$x = \underline{5.4 \text{ horsepower.}}$$

So the motor would be expected to have insufficient power to pass the 50% increased throughput, though it should be able to handle an increase of 40%.

## LECTURE NO. 12

EQUIPMENT FOR SIZE REDUCTION: CUTTERS & GRINDERS, CRUSHERS, GYRATORY CRUSHER, HAMMER MILL, BALL MILL, TUMBLING MILL

### Equipment for Size Reduction

Size reduction equipment is divided into crushers, grinders, ultra fine grinders, and cutting machines.

**Crushers** do the heavy work of breaking large pieces of solid material into small lumps. A primary crusher operates on run-of-mine material, accepting anything that comes from the mine face and breaking it into 150 to 250-mm lumps. A secondary crusher reduces these lumps to particles perhaps 6 mm in size.

**Grinders** reduce crushed feed to powder. The product from an intermediate grinder might pass a 40 mesh screen; most of the product from a fine grinder would pass a 200 mesh screen with a 74  $\mu\text{m}$  opening.

An *ultra fine grinder* accepts feed particles no larger than 6 mm; the product size is typically 1 to 50  $\mu\text{m}$ . *Cutters* give particles of definite size and shape, 2 to 10 mm in length.

These machines do their work in distinctly different ways. Compression is the characteristic action of crushers. Grinders employ impact and attrition, sometimes combined with compression; ultrafine grinders operate principally by attrition.

### Crushers

Crushers are slow-speed machines for coarse reduction of large quantities of solids. The main types are

- jaw crushers,
- gyratory crushers,
- smooth-roll crushers, and
- toothed-roll crushers.

The first three operate by compression and can break large lumps of very hard materials, as in the primary and secondary reduction of rocks and ores.

## **Jaw Crusher**

In a *jaw crusher* the feed is admitted between two jaws, set to form a V open at the top. One jaw is stationary; the other, driven by an eccentric, reciprocates in a horizontal plane and crushes lumps caught between the jaws.

In a *gyratory crusher* a conical crushing head gyrates inside a funnel-shaped casing, open at the top. An eccentric drives the shaft carrying the crushing head. Solids caught between the head and the casing are broken and re-broken until they pass out the bottom.

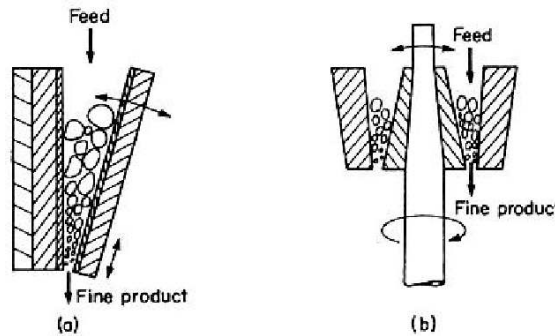


Figure 12.1 a) Jaw Crusher

b) Gyratory crusher

## **Grinders**

The term grinder refers to a variety of size reduction machines for intermediate duty. Product from a crusher is often fed to a grinder for further reduction. Some of the commercial grinders are hammer mills, impactors, rolling compression machines, attrition mills, and tumbling mills.

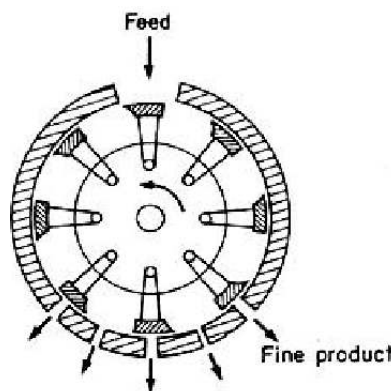


Figure 12.2 Hammer mill

### **Hammer mills:**

These mills all contain a high-speed rotor turning inside a cylindrical casing. Usually the shaft is horizontal. Feed dropped into the top of the casing is broken and falls out through a bottom opening. In a hammer mill, the particles are broken by sets of swing hammers pinned to a rotor disk. A particle of feed

entering the grinding zone cannot escape being struck by the hammers. It shatters into pieces, which fly against a stationary anvil plate inside the casing and break into still smaller fragments. These in turn are rubbed into powder by the hammers and pushed through a grate or screen that covers the discharge opening.

Several rotor disks, 150 to 450 mm in diameter and each carrying four to eight swing hammers, are often mounted on the same shaft. The hammers may be straight bars of metal with plain or enlarged ends or with ends sharpened to a cutting edge. Intermediate hammer mills yield a product 25 mm to 20-mesh in particle size. In hammer mills for fine reduction, the peripheral speed of the hammer tips may reach 110 m/s; they reduce 0.1 to 15 tons/h to sizes finer than 200-mesh. Hammer mills grind almost anything-tough fibrous solids like bark or leather, steel turnings, soft wet pastes, sticky clay, hard rock. For fine reduction they are limited to the softer materials.

The capacity and power requirement of a hammer mill vary greatly with the nature of the feed and cannot be estimated with confidence from theoretical considerations. Commercial mills typically reduce 60 to 240 kg of solid per kilo watt hour of energy consumed.

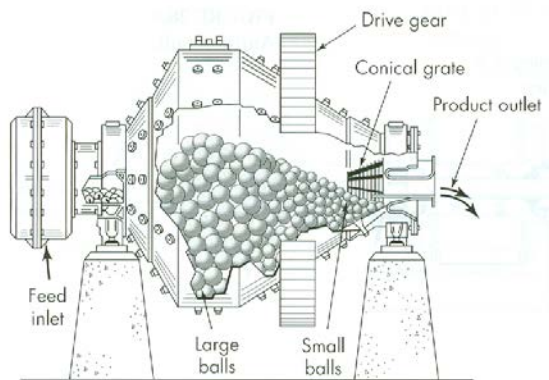


Figure12.3 A conical ball mill

### **Ball Mill**

In a ball mill or pebble mill, most of the reduction is done by impact as the balls or pebbles drop from near the top of the shell. In a large ball mill the shell might be 3 m in diameter and 4.25 m long. The balls are 25 to 125 mm in diameter; the pebbles in a pebble mill are 50 to 175 mm. A tube mill is a continuous mill with a long cylindrical shell, in which material is ground for 2 to 5 times as long as in the shorter ball mill. Tube mills are excellent for grinding to very fine powders in a single pass where the amount of energy consumed is not

of primary importance. Putting slotted transverse partitions in a tube mill converts it into a compartment mill. One compartment may contain large balls, another small balls, and a third pebbles. This segregation of the grinding media into elements of different size and weight aids considerably in avoiding wasted work, for the large, heavy balls break only the large particles, without interference by the fines.

Segregation of the grinding units in a single chamber is a characteristic of the conical ball mill illustrated in above Figure 12.3. Feed enters from the left through a 60° cone into the primary grinding zone, where the diameter of the shell is a maximum. Product leaves through the 30° cone to the right. A mill of this kind contains balls of different sizes, all of which wear and become smaller as the mill is operated. New large balls are added periodically. As the shell of such a mill rotates, the large balls move toward the point of maximum diameter, and the small balls migrate toward the discharge. The initial breaking of the feed particles, therefore, is done by the largest ball dropping the greatest distance; small particles are ground by small balls dropping a much smaller distance. The amount of energy expended is suited to the difficulty of the breaking operation, increasing the efficiency of the mill.

The load of balls in a ball or tube mill is normally such that when the mill is stopped, the balls occupy about one half the volume of the mill. The void fraction in the mass of balls, when at rest, is typically 0.40. The grinding may be done with dry solids, but more commonly the feed is a suspension of the particles in water, increasing both the capacity and the efficiency of the mill.

When the mill is rotated, the balls are picked up by the mill wall and carried nearly to the top, where they break contact with the wall and fall to the bottom to be picked up again. Centrifugal force keeps the balls in contact with the wall and with one another during the upward movement. While in contact with the wall, the balls do some grinding by slipping and rolling over one another, but most of the grinding occurs at the zone of impact, where the free falling balls strike the bottom of the mill.

The faster the mill is rotated, the farther the balls are carried up inside the mill and the greater the power consumption and the capacity of the mill. If the speed is too high, however, the balls are carried over and the mill is said to be centrifuging. The speed at which centrifuging occurs is called the critical speed.

From a balance between the gravitational and centrifugal forces, the critical speed  $n_c$  may be found from the equation

$$n_c = \frac{1}{2\pi} \sqrt{\frac{g}{R-r}}$$

where  $g$  is the acceleration of gravity,  $R$  is the radius of the mill, and  $r$  is the radius of the grinding elements. The operating speed  $n$  must be less than  $n_c$ .

### **ULTRA FINE GRINDERS**

Many commercial powders must contain particles averaging 1 to 20  $\mu\text{m}$  in size, with substantially all particles passing a standard 325-mesh screen that has openings 44  $\mu\text{m}$  wide. Mills that reduce solids to such fine particles are called ultra-fine grinders. Ultra fine wet grinding is done in agitated mills.

### **Cutting machines**

In some size reduction problems the feed stocks are too tenacious or too resilient to be broken by compression, impact, or attrition. In other problems the feed must be reduced to particles of fixed dimensions. These requirements are met by machines known as granulators, which yield more or less irregular pieces, and cutters, which produce cubes, thin squares, or diamonds.

## LECTURE NO. 13

### SEPARATION BY CENTRIFUGATION AND FILTRATION

Foods are complex mixtures of compounds and the extraction or separation of food components is fundamental for the preparation of ingredients to be used in other processes (for example cooking oils from oilseeds or gelatin from connective tissue); or for retrieval of high value compounds, such as enzymes (e.g. papain from papaya for meat tenderisation or rennet from calf stomachs for cheese making) etc.

There are three main categories of separation:

1. Separation of liquids and solids from slurries, pastes, particulates or flours, where either one or both components may be valuable (for example juices, pectin, enzymes, cooking oil, cream and coffee solubles).
2. Separation of small amounts (less than 2%) of solids from liquids. Here the main purpose is purification of water or clarification of liquids such as wine, beer, juices, etc. and the solids are not valuable.
3. Extraction of small amounts of valuable materials using a solvent.

#### **Centrifugation**

There are two main applications of centrifugation: separation of immiscible liquids and separation of solids from liquids. Separation of solid particles from air by centrifugal action is done in the 'cyclone' separator.

Centrifugal force is generated when materials are rotated; the size of the force depends on the radius and speed of rotation and the density of the centrifuged material. In the separation of immiscible liquids, the denser liquid moves to the bowl wall and the lighter liquid is displaced to an inner annulus (Figure 13.1).

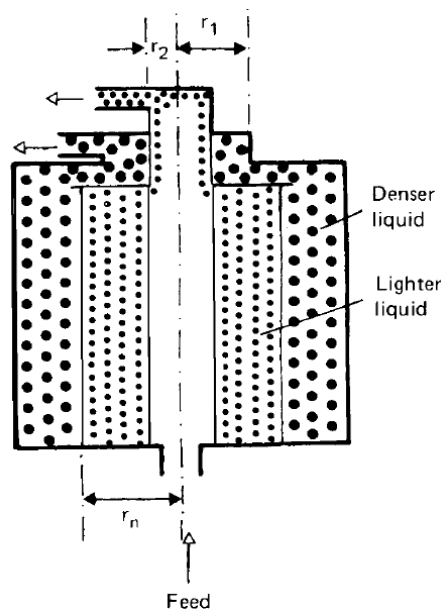


Fig. 13.1 Separation of immiscible liquids:  $r_1$ , radius of dense phase outlet;  $r_2$ , radius of light phase outlet;  $r_n$ , radius of neutral zone.

The thickness of the layers is determined by the density of the liquids, the pressure difference across the layers and the speed of rotation. A boundary region between the liquids at a given centrifuge speed forms at a radius  $r_n$  where the hydrostatic pressure of the two layers is equal. This is termed the neutral zone and is important in equipment design to determine the position of feed and discharge pipes. It is found using:

$$r_n^2 = \frac{\rho_A r_A^2 - \rho_B r_B^2}{\rho_A - \rho_B}$$

where  $\rho$  ( $\text{kg/m}^3$ ) = density and  $r$  (m) = the radius. The subscripts A and B refer to the dense and light liquid layers respectively.

### Sample problem

A bowl centrifuge is used to break an oil-in-water emulsion. Determine the radius of the neutral zone in order to position the feed pipe correctly. (Assume that the density of the continuous phase is  $1000 \text{ kg/m}^3$  and the density of the oil is  $870 \text{ kg/m}^3$ . The outlet radii from the centrifuge are 3 cm and 4.5 cm.)

*Solution :*



$$\begin{aligned}
 r_n &= \sum \left[ \frac{1000(0.045)^2 - 870(0.03)^2}{1000 - 870} \right] \\
 &= \sqrt{\left( \frac{2.025 - 0.783}{130} \right)} \\
 &= 0.097 \text{ m}
 \end{aligned}$$

## Equipment

Centrifuges are classified into **three groups** for:

1. separation of immiscible liquids
2. clarification of liquids by removal of small amounts of solids (centrifugal clarifiers)
3. removal of solids (desludging or dewatering centrifuges).

### ***Liquid–liquid centrifuges***

The simplest type of equipment is the *tubular bowl centrifuge*. It consists of a vertical cylinder (or bowl), typically 0.1 m in diameter and 0.75 m long, which rotates inside a stationary casing at between 15000 rev per min and 50 000 rev per min depending on the diameter. Feed liquor is introduced continuously at the base of the bowl and the two liquids are separated and discharged through a circular weir system into stationary outlets (Fig. 13.1).

### **Disc bowl centrifuge**

Better separation is obtained by the thinner layers of liquid formed in the *disc bowl centrifuge* (Fig. 13.2). Here a cylindrical bowl, 0.2–1.2 m in diameter, contains a stack of inverted metal cones which have a fixed clearance of 0.5–1.27 mm and rotate at 2000–7000 rev/min. They have matching holes which form flow channels for liquid movement. Feed is introduced at the base of the disc stack and the denser fraction moves towards the wall of the bowl, along the underside of the discs. The lighter fraction is displaced towards the centre along the upper surfaces and both liquid streams are removed continuously by a weir system at the top of the centrifuge in a similar way to the tubular bowl system. Disc bowl centrifuges are used to separate cream from milk and to clarify oils, coffee extracts and juices. Disc bowl and tubular centrifuges have capacities of up to 150 000 l/h.

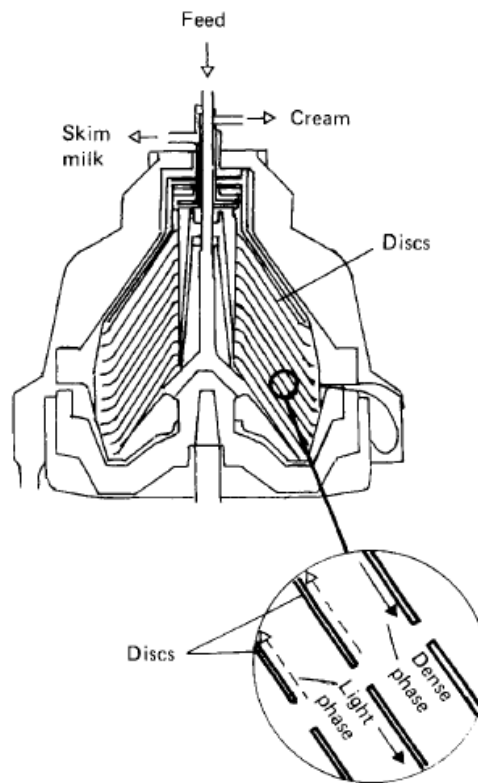


Figure 13.2 Disc bowl centrifuge.

### **Filtration**

Filtration is the removal of insoluble solids from a suspension (or 'feed slurry') by passing it through a porous material (or 'filter medium'). The resulting liquor is termed the 'filtrate' and the separated solids are the 'filter cake'. Filtration is used to clarify liquids by the removal of small amounts of solid particles (for example from wine, beer, oils and syrups).

When a suspension of particles is passed through a filter, the first particles become trapped in the filter medium and, as a result, reduce the area through which liquid can flow. This increases the resistance to fluid flow and a higher pressure difference is needed to maintain the flow rate of filtrate. The rate of filtration is expressed as follows:

$$\text{Rate of filtration} = \frac{\text{driving force (the pressure difference across the filter)}}{\text{resistance to flow}}$$

Assuming that the filter cake does not become compressed, the resistance to flow through the filter is found using

$$R = \mu r \left( \frac{V_c V}{A + L} \right)$$

Where  $R \text{ (m}^{-2}\text{)}$  = resistance to flow through the filter,

$\mu \text{ (N s m}^{-2}\text{)}$  = viscosity of the liquid,

$r \text{ (m}^{-2}\text{)}$  = specific resistance of the filter cake,

$V \text{ (m}^3\text{)} = \text{volume of the filtrate,}$

$V_c = \text{the fractional volume of filter cake in the feed liquid volume, } V$

$A \text{ (m}^2\text{)} = \text{area of the filter and}$

$L = \text{equivalent thickness of the filter and initial cake layer.}$

## Equipment

Gravity filtration is slow and finds little application in the food industry. Filtration equipment operates either by the application of pressure to the feed side of the filter bed or by the application of a partial vacuum to the opposite side of the filter bed. Filter aids are usually applied to the filter or mixed with the food to improve the formation of filter cake.

### Pressure filters

Two commonly used pressure filters are the batch *plate-and-frame filter press* (Fig 13.3) and the *shell-and-leaf pressure filter*.

#### Plate-and-frame filter press

In the plate-and-frame design, cloth or paper filters are supported on vertical plates. Feed liquor is pumped into the press and liquid passes through the filter cloths and flows down the grooved surfaces of the plates to drain through an outlet channel in the base of each plate. A layer of cake builds up on the cloths until the space between the plates is filled. In operation, the pressure is increased to a pre-determined value and the plates are then back-washed with water. The press is dismantled and the cake is removed, ready to begin another cycle. The filter press has relatively low capital costs, high flexibility for different foods, it is reliable and easily maintained. It is widely used for the production of apple juice and cider. However, it is time consuming and highly labour intensive.

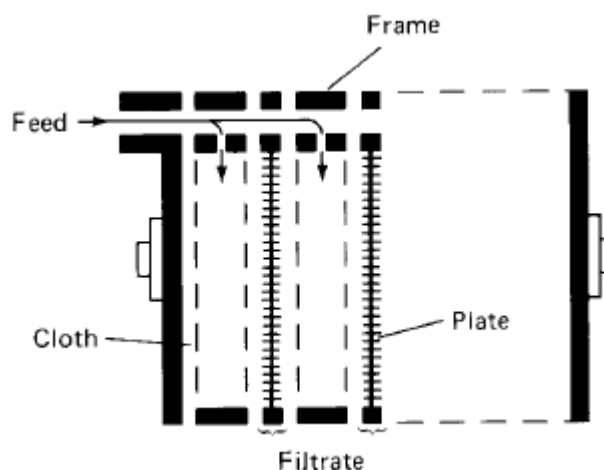


Fig. 13.3 Plate-and-frame filter press.

## LECTURE NO. 14

### SEPARATION BY EXPRESSION, EXTRACTION USING SOLVENTS

#### **Expression**

The main applications of expression are in the extraction of components plant materials either for direct consumption (for example fruit juices) or for use in subsequent processing (for example sugar, grape juice for wine and vegetable oils). These materials are located within the cell structure of the plants and it is necessary to disrupt the cells in order to release them. This is achieved either in a single-stage, which both ruptures the cells and expresses the liquid, or in two stages (size reduction to produce a pulp or flour, followed by separation in a press). In general the single-stage operation is more economical, permits higher throughputs and has lower capital and operating costs, but for some products that are especially hard (for example oil bearing nuts) a two-stage expression is more effective. Better extraction is achieved by heating oilseeds or flours to reduce the oil viscosity, release oil from intact cells and remove moisture. There is optimum moisture content for each type of oil seed to obtain a maximum yield of oil.

In fruit processing, the press should remove the maximum quantity of juice, without substantial quantities of solids, or phenolic compounds from the skins which cause bitterness and browning. This is achieved using lower pressures and fewer pressings. It is also necessary to increase the pressure slowly to avoid the formation of a dense impenetrable press cake, as the solid material is easily deformed and blocks the press.

The factors that influence the juice yield from a press include:

- maturity and growth conditions of the raw material
- extent of cell disruption
- thickness of the pressed solids and their resistance to deformation
- rate of increase in pressure, the time of pressing and the maximum pressure applied
- temperatures of solids and liquid and the viscosity of the expressed liquid.

#### **Equipment**

##### ***Batch presses***

Common types of equipment for expressing juice or oils are the *tank press* and the *cage press*.

## Tank press

The tank press is used for fruit juice production and consists of a horizontal cylinder which is divided internally by a membrane. During an automatically controlled pressing cycle of 1.5 h, fruit pulp is fed into one side of the membrane and compressed air is applied to the opposite side (Figure.14.1). Juice flows out through channels and, when pressing is completed, the tank is rotated to loosen and discharge the press residue. High yields of good-quality juice are obtained by the gentle increase in pressure at capacities ranging from 3600 kg to 25 000 kg.

In the cage press, up to 2 t of fruit pulp or oilseed flour is placed into a vertical perforated or slatted cage, either loose or in cloth bags depending on the nature of the material. In larger presses, ribbed layer plates are used to reduce the thickness of the pulp or flour bed. The pressure is gradually increased on the top plate by an hydraulic system or motor-driven screw thread and liquid is collected at the base of the press. The equipment allows close control over the pressure exerted on the pulp/flour and may operate semi-automatically to reduce labour costs.

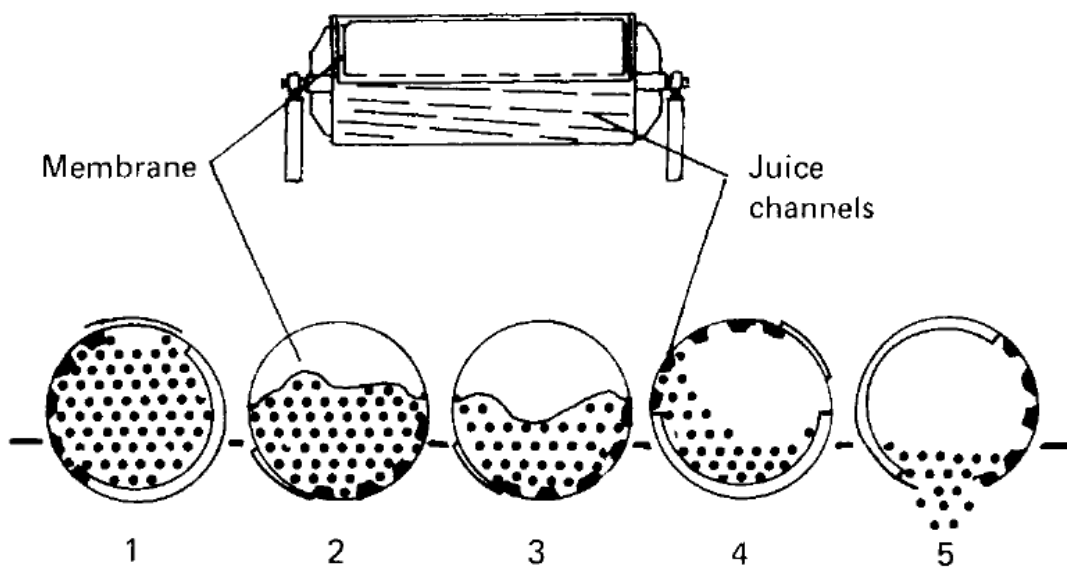


Figure 14.2 Tank press: 1, tank filled; 2, membrane partly inflated; 3, membrane further inflated; 4, loosening residue; 5, discharge.

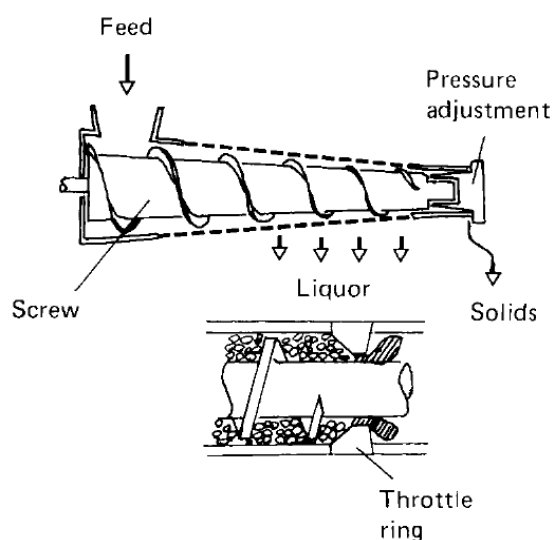


Figure 14.3 Screw press, showing throttle ring used for oilseed pressing.

### ***Continuous presses***

There are several types of continuous press used commercially: the belt press for fruit processing, the screw expeller for both fruit processing and oil extraction, and the roller press for sugar cane processing.

#### **Screw expeller**

The *screw expeller* consists of a robust horizontal barrel containing a stainless steel helical screw (Figure 14.4). The pitch of the screw flights gradually decreases towards the discharge end, to increase the pressure on the material as it is carried through the barrel. The final section of the barrel is perforated to allow expressed liquid to escape. Press cake is discharged through the barrel outlet and the pressure in the barrel is regulated by adjusting the diameter of the discharge port. Frictional heat reduces the viscosity of the oil and some types of expellers have supplementary heaters fitted to the barrel to improve yields. In juice extraction the barrel is cooled to reduce the friction heat, generated by the movement of food, which may have an undesirable effect on flavour and aroma. Capacities range from 40 kg/h to 8000 kg/h. The oil cake has 5–18% (w/w) **residual oil, depending on the type of oil-seed and the operating conditions.**

### **Extraction using solvents**

Unit operations that involve separation of specific components of foods are important in a number of applications, including production of:

- cooking oils or specialty oils from nuts and seeds

- flavors and essential oils (e.g. black pepper, cardamom, clove, ginger, hops, parsley, vanilla, etc.)
- coffee
- sugar
- removal of caffeine from coffee and tea.

Once the solvent has been removed from the extracted foods, some may be used directly (for example cooking oils) or they may be further processed by concentration and/or dehydration.

The main types of solvents used for extraction are water, organic solvents or supercritical carbon dioxide.

Solid-liquid extraction involves the removal of a desired component (the solute) from a food using a liquid (the solvent) which is able to dissolve the solute. This involves mixing the food and solvent together, either in a single stage or in multiple stages, holding for a pre-determined time and then separating the solvent. During the holding period there is mass transfer of solutes from the food material to the solvent, which occurs in three stages:

1. the solute dissolves in the solvent
2. the solution moves through the particle of food to its surface
3. the solution becomes dispersed in the bulk of the solvent.

During extraction, the holding time should therefore be sufficient for the solvent to dissolve sufficient solute and for the changes in composition to approach an equilibrium. The time required depends on the solubility of a given solute in the solvent selected and also on the following factors:

- The temperature of extraction: Higher temperatures increase both the rate at which solutes dissolve in the solvent and the rate of diffusion into the bulk of the solvent. The temperature of most extraction operations is limited to less than 100°C by economic considerations, extraction of undesirable components at higher temperatures or heat damage to food components.
- The surface area of solids exposed to the solvent. The rate of mass transfer is directly proportional to the surface area, so reductions in particle size (giving an increase in surface area) increase the rate of extraction up to certain limits.
- The viscosity of the solvent. This should be sufficiently low to enable the solvent to penetrate easily the bed of solid particles.

- The flow rate of the solvent. Higher flow rates reduce the boundary layer of concentrated solute at the surface of particles and thus increase the rate of extraction.

Table 14.1 : Solvents used to extract food components

| Food                                                                                       | Solvent                                                   | Final solute concentration (%) | Temperature (°C)                                         |
|--------------------------------------------------------------------------------------------|-----------------------------------------------------------|--------------------------------|----------------------------------------------------------|
| Decaffeinated coffee                                                                       | Supercritical carbon dioxide, water or methylene chloride | N/A                            | 30–50 (CO <sub>2</sub> )                                 |
| Fish livers, meat byproducts                                                               | Acetone or ethyl ether                                    | N/A                            | 30–50                                                    |
| Hop extract                                                                                | Supercritical carbon dioxide                              | N/A                            | <100–180                                                 |
| Instant coffee                                                                             | Water                                                     | 25–30                          | 70–90                                                    |
| Instant tea                                                                                | Water                                                     | 2.5–5                          | N/A                                                      |
| Olive oil                                                                                  | Carbon disulphide                                         | N/A                            |                                                          |
| Seed, bean and nut oils (e.g. from soybeans, groundnuts, cottonseed, sunflower seed, etc.) | Hexane, heptane or cyclohexane                            | N/A                            | 63–70 (hexane)<br>90–99 (heptane)<br>71–85 (cyclohexane) |
| Sugar beet                                                                                 | Water                                                     | approx. 15                     | 55–85                                                    |

*Adapted from data of Brennan et al. (1990) and Clarke (1990).*



## LECTURE NO. 15

### MEMBRANE CONCENTRATION (HYPERFILTRATION AND ULTRAFILTRATION)

Reverse osmosis (RO) (or 'hyperfiltration') and ultrafiltration (UF) are both unit operations in which water and some solutes in a solution are selectively removed through a semi-permeable membrane. They are similar in that the driving force for transport across the membrane is the pressure applied to the feed liquid. However, reverse osmosis is used to separate water from low-molecular-weight solutes (for example salts, mono-saccharides and aroma compounds), which have a high osmotic pressure. A high pressure, five to ten times that used in UF ( $4000\text{--}8000 \times 10^3 \text{ Pa}$ ), is therefore necessary to overcome this (hence the term *reverse osmosis*).

The largest commercial food application of reverse osmosis is the concentration of whey from cheese manufacture, either as a pre-concentration stage prior to drying or for use in the manufacture of ice cream. Reverse osmosis is also used to:

- concentrate and purify fruit juices (Robe, 1983), enzymes, fermentation liquors and vegetable oils
- to concentrate wheat starch, citric acid, egg white, milk, coffee, syrups, natural extracts and flavors
- to clarify wine and beer
- to demineralise and purify water from boreholes or rivers or by desalination of sea water.

In the last application, monovalent and polyvalent ions, particles, bacteria and organic materials with a molecular weight greater than 300 are all removed by up to 99.9% to give high-purity process water for beverage manufacture and other applications.

Other applications include 'dealcoholisation' to produce low-alcohol beers, cider and wines, and recovery of proteins or other solids from distillation residues, dilute juices, waste water from corn milling or other process wash waters. Membrane pre-concentration is also used to prepare coffee extracts and liquid egg for drying and to pre-concentrate juices and dairy products before evaporation, so improving the economy of evaporators. Concentrating fluids by removal of water at low temperatures in the dairy, fruit juice and sugar

processing industries competes with vacuum evaporation and freeze concentration. The advantages of membrane concentration over concentration by evaporation are:

- the food is not heated, and there is therefore negligible loss of volatiles or changes to nutritional or eating quality
- in contrast with boiling, membrane concentration does not involve a change in phase and therefore uses energy more efficiently (Table 6.4)
- simple installation with lower labour and operating costs
- no requirement for steam boilers.

The main limitations of membrane concentration are:

- variation in the product flow rate when changes occur in the concentration of feed liquor
- higher capital costs than evaporation
- a maximum concentration to 30% total solids
- fouling of the membranes (deposition of polymers), which reduces the operating time between membrane cleaning.

Different types of membrane reject solutes with specific ranges of molecular weight. These molecular weight 'cut-off' points are used to characterize membranes.

For reverse osmosis membranes, the cut-off points range from molecular weights of 100 Da at 4000–7000  $\times 10^3$  Pa to 500 Da at 2500–4000  $\times 10^3$  Pa.

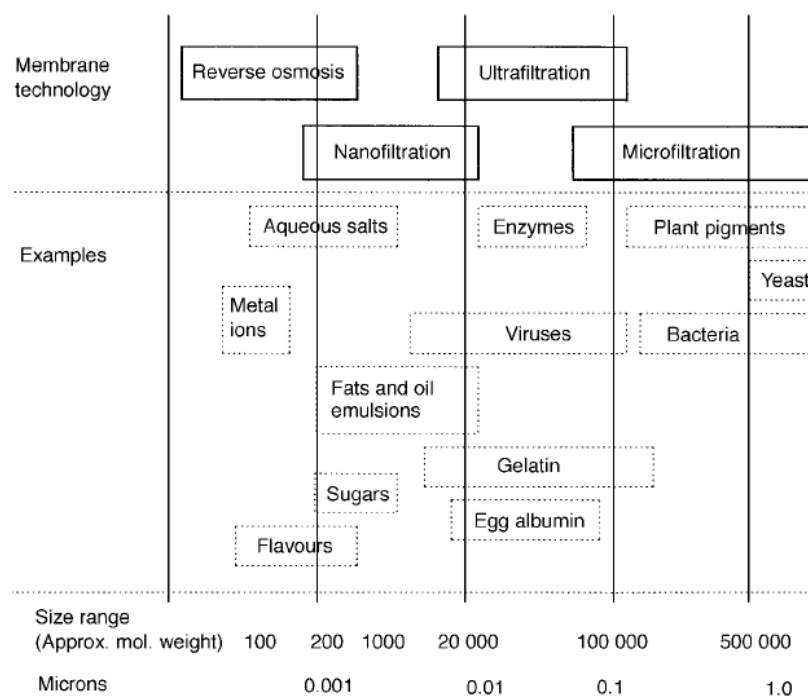


Figure 15.1 Size separation capabilities of different membrane systems.

The term *nanofiltration* (NF) (or 'loose reverse osmosis') is used when membranes remove materials having molecular weights in the order of 300–1000 Da (Rosenberg, 1995). This compares to a molecular weight range of 2000–300 000 for ultrafiltration membranes, although above 30 000 there is overlap with microfiltration (Fig.15.2). NF is capable of removing ions that contribute significantly to the osmotic pressure and thus allows operation at pressures that are lower than those needed for RO.

## LECTURE NO. 16

### INTRODUCTION AND IMPORTANCE OF PHYSICAL PROPERTIES-SHAPE AND SIZE OF GRAINS, SHAPE AND SIZE OF FRUITS, BULK DENSITY OF THE GRAINS, TRUE DENSITY OF THE GRAINS, POROSITY, ANGLE OF REPOSE, TEST WEIGHT

#### Introduction and Importance of Engineering Properties

*The knowledge of physical properties such as shape, size, volume, surface area, test weight, density, porosity, angle of repose, etc., of different grains is necessary for the design of various equipment for handling, processing and storage of grains.*

#### **SHAPE AND SIZE**

Shape of the grain is connected with the geometrical form of the grain. Size of the grain refers to the characteristics of an object which in term determine how much space it occupies and, within limits, can be described in terms of length, width, and thickness. The Shape and size together with other characteristics of the grains is important in the design of the seed grader. These factors determine the free flowing or bridging tendencies of the seed mass, and therefore, determine the suitable handling and feeding equipment. Sphericity and equivalent diameters are also used to describe the shape and size, respectively for the grains.

The sphericity ( $\phi$ ) defined as the ratio of the surface area of sphere having the same volume as that of the grain to the surface area of the grain, can be calculated from the axial dimensions of the grain as follows:

$$\phi = \frac{(l_i b_i t_i)^{1/3}}{l_i} \quad \text{-----} \quad (16.1)$$

Equivalent diameter ( $D_p$ ) of the grain, considering a prolate spheroid shape for grains, can be calculated through the following expression:

$$D_p = \left[ 4l_i \left( \frac{b_i + t_i}{4} \right)^2 \right]^{1/3} \quad \text{-----} \quad (16.2)$$

The sphericity ( $\phi$ ) of the fruits can be calculated using the following formula.

$$\phi = \frac{(abc)^{1/3}}{a} \quad \text{-----} \quad (16.3)$$

Where,

(a) = major diameter

(b) = intermediate diameter

(c) = minor diameter

The geometrical mean diameter (GMD) can be calculated as follows:

$$GMD = (abc)^{1/3} \text{ ----- (16.4)}$$

Grain shape tester or grain vernier is used for grains whereas vernier Calipers having least count of 0.01 mm is used to take dimensions of fruits.

### THE BULK DENSITY

The bulk density ( $\rho_b$ ) considered as the ratio of the weight of the grain in kg to its total volume in  $m^3$ . The bulk density of grains is measured using 1 liter measuring cylinder and electronic balance. The bulk density of the food grains changes with the change in the moisture content. Hence, the moisture content of the food grains at which the bulk density was measured also to be reported. The bulk density can be calculated using the following formula.

$$\rho_b = \frac{W_s}{V_s} \text{ ----- (16.5)}$$

where,

$\rho_b$  = bulk density,  $kg/m^3$ ,

$W_s$  = weight of sample, kg and

$V_s$  = volume of the sample i.e., 1000 cc or  $10^{-3} m^3$

### TRUE DENSITY

The true density ( $\rho_t$ ) defined as the ratio of mass of the sample (W) to its true volume. The true density ( $\rho_t$ ) is determined using a Multivolume Pycnometer (Helium gas displacement method). Multivolume Pycnometer's Helium displacement method provides a rapid means for precisely determining the true volume of pores, porous materials, and irregularly shaped food grains. The true density of the grains is found to be decreased with an increase in moisture content as the increase in true volume of the grains is higher compared to the increase in moisture content of the grains. Since, the true density varies with the moisture content of the food grains, the moisture content of the food grains also to be reported.

True density can be calculated using following formula.

$$\text{True density, } \rho_t = \frac{\text{Total mass of the grain, kg}}{V_{\text{samp}}} \text{----- (16.6)}$$

Multivolume pycnometer is used to measure the true volume.

### POROSITY

Properties such as bulk density, true density and porosity of grains are useful in design of various separating, handling, storing and drying systems. Resistance of bulk grain to airflow is a function of the porosity and the kernel size.

The porosity ( $\varepsilon$ ) defined as the percentage of void space in the bulk grain which is not occupied by the grain can be calculated from the following relationship:

$$\varepsilon = \frac{\rho_t - \rho_b}{\rho_t} \times 100 \text{-----}$$

(16.7)

where,

$\varepsilon$  = porosity

$\rho_b$  = bulk density, kg/m<sup>3</sup>

$\rho_t$  = true density, kg/m<sup>3</sup>

### ANGLE OF REPOSE

Angle of repose is important in designing a structure for storage of food grains in bulk. When a granular material is allowed to flow freely from a point into a pile, the angle which the side of the pile makes with horizontal plane is called the angle of repose (IS: 6663-1972).

The angle of repose is influenced by size, shape, moisture content and orientation of the particles. It has been found that the angle of repose increases with the increase in moisture content. The cohesive materials have larger angle of repose. Lower angle of repose represents easier flowability.

Angle of repose of the grain can be calculated experimentally using the following formulae:

$$\theta = \tan^{-1} \left( \frac{2H_c}{D_c} \right) \text{-----}$$

(16.8)

where,

$H_c$  = height of cone formed measured with depth gauge

$D_c$  = diameter of the platform on which the cone formed

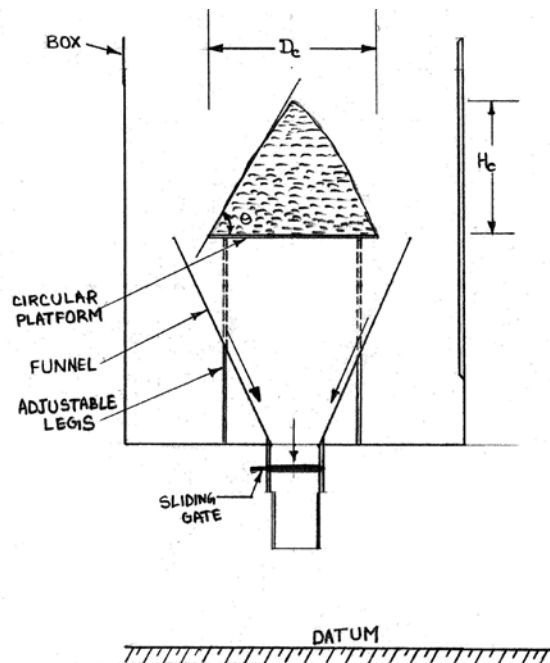


Fig. 16.1 Line diagram of Experimental Set up for Angle of Repose

### TEST WEIGHT OF THE GRAINS

Test weight is the weight of test sample per unit sample and is direct indication of bulk density. It is closely related to kernel weight. It is a useful index to milling outturn in measuring the relative amount of dockage or foreign material in given lot of paddy. It is also useful in measuring the amount of shriveled or immature kernels and in estimating the weight contained in a storage bin of given volume. Test weight is the easiest and most convenient method of estimating quality of paddy during procurement.

## LECTURE NO. 17

CO-EFFICIENT OF EXTERNAL FRICTION, CO-EFFICIENT OF INTERNAL FRICTION, COLOUR OF FOOD MATERIALS

### COEFFICIENT OF STATIC FRICTION

The frictional properties of granular materials are important in designing of storage bins, hoppers, chutes, pneumatic conveying system, screw threshers and conveyors, forage harvesters, etc,. The ratio between the force of friction (F), and the force normal to the surface of contact (N), is known as the coefficient of friction ( $\mu$ ).

Mathematically,

$$\text{Coefficient of friction, } \mu = \frac{F}{N}$$

where,

F = Frictional force (Amount of total Weights added + Suspended Pan )

N = Normal Load (Weight of the material + Circular Ring)

### COEFFICIENT OF INTERNAL FRICTION

The friction of the kernels or grains against each other is known as internal friction where as the friction between the grain mass and the contact surface is known as static friction. The coefficient of the internal friction of the grains is required in predicting the lateral pressure on a retaining wall in silos or design of silos and hoppers for gravity flow. The method employed for the determination of the coefficient internal friction is by tri-axial compression test apparatus or Shear test apparatus.

The direct shear test apparatus consists of a shear cell, a controlled loading device and a recorder. The normal load is applied by weights acting vertically. The shearing action is provided by means of an electrical or mechanical drive with a load cell or dynamometer in line for force measurement. The shearing force acts in the plane of contact between the base and the ring. The shear cell assures a uniform stress distribution across the specimen sample and shear of solid in the plane between the ring and base.



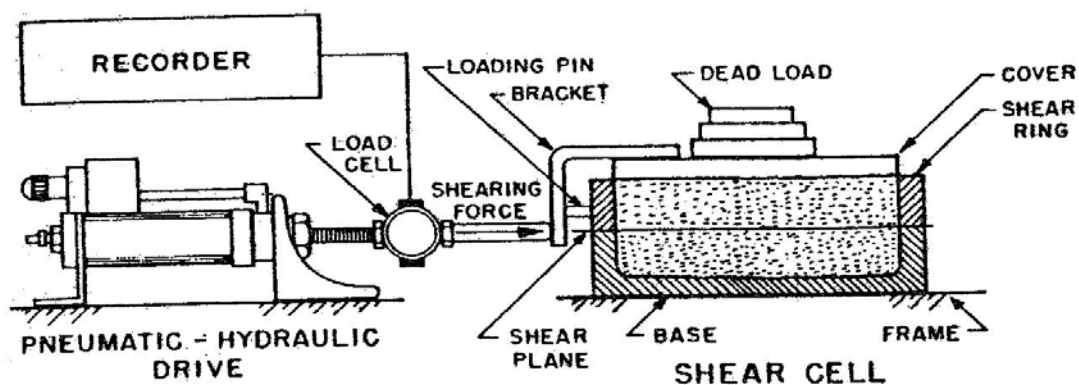


Fig. 17.1 Experimental set up for coefficients of internal friction

Shear test apparatus is used to estimate the coefficient of internal friction of the grains.

### COLOUR

The optical properties such as light transmittance and reflectance properties of fruits or grains are important in electronic sorting and grading, maturity, and surface color determinations. The surface color of the fruits and food grains are measured using the Hunter Lab in terms of CIE 'L', 'a' and 'b' values. Hunter scale, L measures lightness and varies from 100 for perfect white to zero for black, approximately as the eye would evaluate it. The chromaticity dimensions (a and b) give understandable designations of color as follows, 'a' measures redness when positive, gray when zero, and greenness when negative. 'b' measures yellowness when positive, gray when zero, and blue when negative.

## **LECTURE NO. 18**

THE NEED TO CONSIDER HYGIENIC DESIGN, HAZARDS, HOW TO APPROACH HYGIENIC DESIGN, HYGIENIC DESIGN PRIORITIES, HYGIENIC DESIGN PRINCIPLES, SOME GENERAL DESIGN POINTERS

### **Hygienic Design of Food Processing Equipment**

#### **The need to consider hygienic design**

The need to consider hygienic design at the specifying (if purchasing) and designing (if manufacturing) stages is now crucial as users face increasing potential problems from loss of product through spoilage, food safety fears and loss of market confidence. Their prime needs are ease of access and ease of cleaning.

#### **Hazards**

Food safety hazards can arise from:

- microbiological causes such as pathogens, spoilage organisms or toxins;
- chemicals such as cleaning agents, disinfecting agents and lubricants;
- foreign bodies such as raw materials, pests and materials used in the construction of the machinery.

#### **How to approach hygienic design**

#### ***Machinery makers/suppliers***

A risk assessment should be undertaken by the machine manufacturer at the design stage as different products at different stages of processing give rise to different levels of food safety risk and need different levels of rigour in engineering the hygiene controls. Low-risk product / process machinery may need only to partially conform to best engineering practice. However, high-risk product/process machinery will need to fully conform to design requirements set in Standards (see References) and operate within set heat, chemical or physical treatment limits and require planned disassembly for cleaning.

#### ***Hygienic risk factors to consider***

- Purpose of the machine (is it intended for a single type of food)

- Nature of the food (is it raw material or ready for consumption)
- Stage of processing (will the machine only handle raw materials or produce the final product)
- Stage of the food (will it be consumed immediately or have a defined shelf life)
- Consumer of the food (is the food intended for vulnerable groups such as children or the elderly)
- Market (is the food intended for local or international markets)
- Use of the machine (will it be used infrequently, or be in continuous use)
- Cleaning and inspection (will this be done routinely during the day or once a week)

### **Machinery users**

Intending users of equipment will be undertaking their own analysis of food safety risks which can help them decide the hygienic design risk specification they need. Users will need to ensure there is a good match between the level of good hygienic design they need in the process for the product and the level of hygienic design offered by the equipment. Ideally, users should set a specification for the supplier or maker to match. However, if this is not possible, and for series production machines, the maker can specify the risk levels the machine has been designed for through limits of intended use and safe applications. It is then down to the user to select only suitable machinery for use.

### **Hygienic design priorities**

Those machines for products and processes which pose the highest food safety risks to consumers need to have their hygienic design needs considered more rigorously and in more depth.

The main hygienic design priorities to any machinery, and its cleaning-in-place (CIP) system, is intended or could be used for:

- liquid filling, especially in the dairy industry;
- dairy products;
- cooked meat;
- short shelf-life, chilled foods;
- finished salads;
- conveyor systems for unpacked product;
- meat slicers;
- ice cream production post-pasteurisation;
- cook chill production;
- sandwich manufacture;
- pork pie and pastry production; and
- dust control units and silos (infestation risks).

### **Hygienic design principles**

The broad principles can be summarized as follows:

- firstly, establish whether the food safety risk can be eliminated by design and construction methods which are state of the art;
- if not, reliance has to be placed on cleaning and disinfection regimes - these need to be given to the user in instructions from the maker and the machine designed to allow easy and effective cleaning;
- if not, limitations need to be given in instructions to the user on use of the machine (temperature, product etc).

### **Some general design pointers**

#### **Do's:**

- Ensure that the materials and surfaces food will come into contact with are suitable (eg. corrosion resistant, non-absorbent, unpainted and easy to clean) - such materials must not be likely to break, crack or fracture in normal use.

- Ensure surfaces food will come into contact with are made of non-toxic materials which will not transfer any odor, taint or taste to the product.
- Ensure permanent joints are smooth where joints are in the same plane or curved where they are not.
- Ensure dismountable joints have a true and hygienic fit.
- Ensure projections, edges and recesses are kept to a minimum.
- Ensure internal curves allow thorough cleaning and, where necessary, disinfection.
- Ensure all fluids, including those from foods and cleaning the machine, can be easily discharged from the machine.
- Ensure shafts and seals are self- or product lubricated or use food grade lubricants - ensure they can be cleaned and, where necessary, disinfected.
- Ensure appropriate materials are used in the machine construction - there may be a balance between ease of access for effective cleaning indicating ordinary steel could be used and lack of such access (eg. in enclosed plant) indicating stainless steel could be used.

**Don'ts:**

- Don't allow dead spaces or bends in pipe work in the food area which allow product to accumulate if this is unavoidable, then ensure good drainage and cleanability.
- Don't allow bearings in the food area unless this is unavoidable - use food grade lubricants and ensure cleanability and, where necessary, disinfectability.
- Don't use screws, screw heads and rivets in contact with food.
- Don't allow liquids, pests or organic matter to enter parts of machines which cannot be cleaned.
- Don't allow ancillary substances (eg. lubricants) to come into contact with the food.

## LECTURE NO. 19

SOME BASIC CONCEPTS OF RHEOLOGY, BIOLOGICAL SYSTEMS AND MECHANICAL PROPERTIES, ASTM STANDARD DEFINITION OF TERMS RELATED TO MECHANICAL PROPERTIES

### SOME BASIC CONCEPTS OF RHEOLOGY

**MECHANICAL PROPERTIES** are defined as those having to do with the behavior of the material under applied forces. Following this broad definition, such properties as stress strain behavior of a material under static and dynamic loading as well as flow characteristics of the material in air or in water, can be classified as mechanical properties.

**Rheology** has been defined as "a science devoted to the study of **deformation** and **flow**." Therefore, when the action of forces result in deformation and flow *in the material*, the mechanical properties will be referred-to as rheological properties. Moreover, rheology considers the time effect during the loading of a body. Rheologically then, mechanical behavior of a material is expressed in terms of the three parameters of force, deformation and time. **Examples of rheological properties** are time-dependent stress and strain behavior, creep, stress relaxation, and viscosity.

### BIOLOGICAL SYSTEMS AND MECHANICAL PROPERTIES

Each unit of the food and feed materials selected from agricultural products is in itself a biological system which differs from identical mass-produced products. These materials are alive, constantly undergoing changes in shape, size, respiration, and other aspects of life processes. During development and storage, the cells are sensitive to such external influences as humidity, temperature, oxygen, food supply, energy consumption, as well as the interplay of internal factors which are difficult to control. In biological solids elasticity varies with age and physiological conditions. Biological fluids are mostly non-Newtonian liquid which cause additional complications.

As a result of this complex situation, in studying the rheology of a biological system, only an empirical approach-is possible.

### ASTM STANDARD DEFINITION OF TERMS RELATED TO MECHANICAL PROPERTIES

#### ***Strain***

The unit change, due to force, in the size or shape of a body referred to its original size or shape. Strain is a non dimensional quantity, but it is frequently expressed centimetres per centimetre, m/m, mm/mm etc.

a. **Linear (tensile or compressive) strain:** The change per unit length due to force in an original linear dimension.

b. **Axial strain:** Linear strain in a plane parallel to the longitudinal axis of the specimen.

c. **Transverse strain:** Linear strain in a plane perpendicular to the axis of the specimen.

d. **Shear strain (angular strain):** The tangent of the angular change, due to force, between two lines originally perpendicular to each other through a point in a body.

e. **True strain:** In a body subjected to axial force, the natural logarithm of the ratio of the gauge length at the moment of observation to original gauge length.

f. **Macro strain:** The mean strain over any finite gauge length of measurement large in comparison with inter atomic distances.

### **Stress**

The intensity of a point in a body of the internal forces or components of force that act on a given plane through the point. Stress is expressed in force per unit of area (kilograms-force per square millimeter).

a **Nominal stress:** The stress at a point calculated on the net cross section by simple elastic theory without taking into account the effect on the stress produced by geometric discontinuities such as holes, grooves, fillets etc.

b **Normal stress:** The stress component perpendicular to a plane on which the forces act. Normal stress may be either:

1 **Tensile stress:** Normal stress due to forces directed away from the plane on which they act, or

2 **Compressive stress:** Normal stress due to forces directed towards the plane on which they act.

c **Shear stress :** The stress component tangential to the plane on which the forces act.

d **Torsional stress:** The shear stress on a transverse cross section resulting from a twisting action.

**e True stress** : The axial stress in a tension or compression test, calculated on the basis of the instantaneous cross sectional area instead of the original area.

**f. Principal stress (normal):** The maximum or minimum value of the normal stress at a point in a plane considered with respect to all possible orientations of the considered plane. On such principal planes the shear stress is zero.

**g. Fracture stress:** The true normal stress on the minimum cross sectional area at the beginning of fracture.

### ***Bearing load***

A compressive load on an interface.

### ***Compressive strength***

The maximum compressive stress which a material is capable of sustaining. Compressive strength is calculated from the maximum load during a compression test and the original cross sectional area of the specimen.

### ***Elastic Limit***

The greatest stress which a material is capable of sustaining without any permanent strain remaining upon complete release of the stress.

### ***Modulus of elasticity***

The ratio of stress to corresponding strain below the proportional limit.

*(Note)For materials where the stress-strain relationship is curvilinear rather than Linear, one of the four following terms may be used):*

**a Initial tangent modulus:** The slope of the stress-strain curve at the origin.

**b Tangent modulus** : The slope of the stress-strain curve at any specified stress or strain.

**c Secant modulus** : The slope of the secant drawn from the origin to any specified point on the stress-strain curve.

**d Chord modulus:** The slope of the chord drawn between any two specified points on the stress - strain curve.

### **Poisson's ratio**



The absolute value of the ratio of transverse strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit of the material.

### ***Proportional Limit***

The greatest stress which a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooker's law).

### ***Set***

Strain remaining after complete release of the load producing the deformation ***Shear strength***

The maximum shear stress that a material is capable of sustaining. Shear strength is calculated from the maximum load during a shear or torsion test and is based on the original dimensions of the cross section of the specimen.

### ***Tensile strength***

The maximum tensile stress that a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried "to rupture and the original cross sectional area of the specimen.

### ***Yield point***

The first stress in a material, less than the maximum attainable stress, at which an increase in strain occurs without an increase in stress.

## LECTURE NO. 20

### OTHER DEFINITIONS RELATED TO MECHANICAL PROPERTIES

#### Pressure

A measure of the mean normal stress on a point of body ( $\text{kg} / \text{cm}^2$ )

#### Deformation

Deformation or distortion is the **relative displacement of points** within a body. Deformation like stress is a **vector quantity**. In general, deformation is **accompanied** either by **change of volume** or by **change of shape**. The change of volume is caused by **isotropic stress** such as hydrostatic pressure. The change of shape is brought about by **shear stresses**. Material can be deformed by uniaxial compression, uniaxial tension, shear, and bulk compression:

#### Bioyield point

A point, such as y in Figure 20.1 on the stress-strain or force-deformation curve at which there occurs an increase in deformation with a decrease or no change of force. In some agricultural products, the presence of this bioyield point is an indication of initial cell rupture in the cellular structure of the material. The term bioyield point is proposed for biological materials to differentiate this phenomenon from the yield point in engineering materials. The bioyield point may occur at any point beyond the point LL, where the curve deviates from the initial straight line portion.

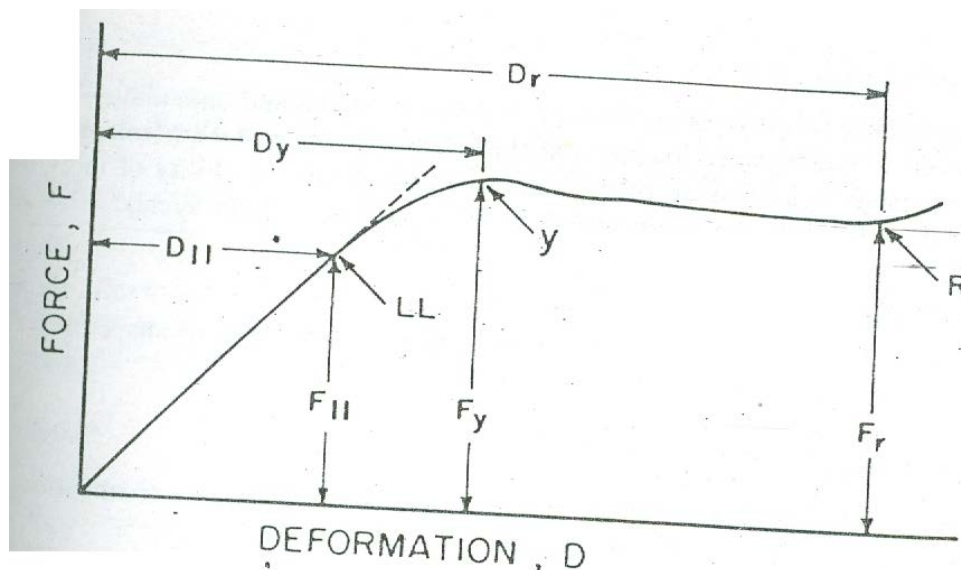


Figure 20.1. A possible force-Deformation curve for an agricultural product. LL linear limit; y, "Bioyield point";, R, rupture point

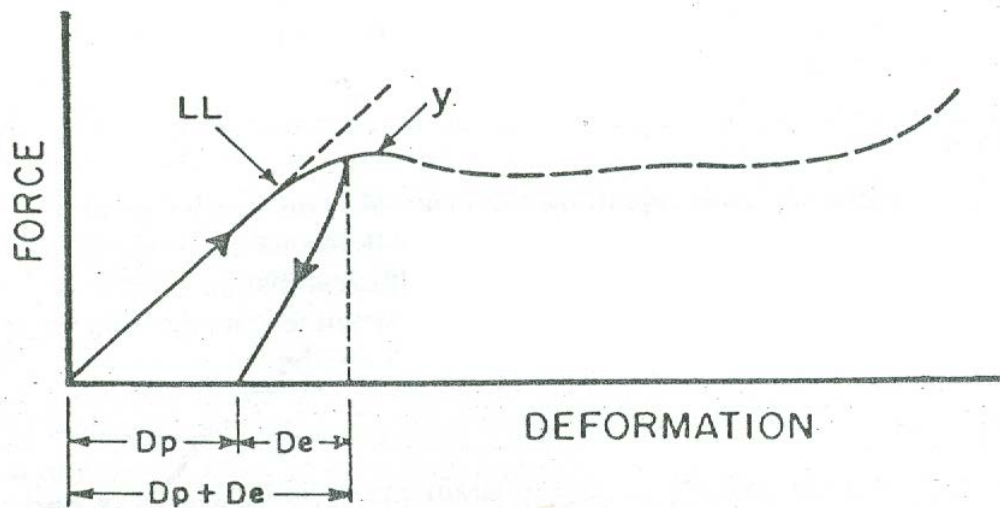


Figure 10. 2 Degree of elasticity from a loading-unloading curve.  $D_e$  = elastic or recoverable deformation;  $D_p$  = plastic or residual deformation;  $\frac{D_e}{D_p + D_e}$  = degree of elasticity

### Rupture point

A point on the stress-strain or force-deformation curve at which the axially loaded specimen ruptures under a load. In biological materials, rupture may cause puncture of shell or skin, cracking, or fracture planes. It may be stated that a "**bioyield point**" in these materials corresponds to a **failure in the microstructure** while a "**rupture point**" corresponds to a failure in the **macrostructure** of the specimen. In a force-deformation curve such as **Figure 20.1**, the point of rupture of the specimen may occur at any-point on the curve beyond the bioyield point. In a "brittle" material, rupture may occur in the early portion of the curve. In a "tough" material, rupture may take place after considerable plastic flow at such point as R.

### Stiffness

**Stiffness** or **rigidity** is indicated by the slope of the initial straight line portion of the curve (Figure 20.1). The ratio of stress to strain in this more or less elastic region of the curve may be referred to as the "modulus of elasticity" or "Young's modulus" ( $\text{kg/cm}^2$ ). In the case of nonlinear stress-strain behavior, stiffness or "apparent modulus" can be defined in terms of initial tangent modulus, secant modulus, or tangent modulus, as illustrated in Figure 3. Initial tangent modulus is taken as the slope of the curve at the origin. Secant modulus is the slope of the line connecting the origin and a selected point A on the curve.

Tangent modulus is the slope of the tangent line to a selected point B on the curve.

### **Elasticity**

The capacity of a material for taking elastic or recoverable deformation. In those portions of the curve in **Figure 20.1** before the point LL is reached, elongations are, in large part at least, recoverable, and are a measure of elastic deformation.

### **Plasticity**

The capacity of a material for taking plastic or permanent deformation. Since deformations from the bioyield point to the point of rupture are not all recoverable, the unrecoverable part can be taken as a measure of plastic deformation (Figure 20.2).

### **Degree of elasticity**

The ratio of elastic deformation to the sum of elastic and plastic deformation when a material is loaded to a certain load and then unloaded to zero load (Figure 20.2).

### **Strength**

The resistance to applied force (kg/cm).

### **Ultimate strength**

The stress corresponding to the rupture point (kg/cm<sup>2</sup>).

### **Bioyield strength**

The stress corresponding to the bioyield point.

### **Toughness**

The work required to cause rupture in the material. This can be approximated by the area under the stress-strain or force-deformation curve up to the point selected as the rupture point (cm-kg/cm<sup>3</sup>). If in estimating toughness, a force-deformation curve is used, the size of the specimen and the loading surface area should be specified.

### **Resilience**

The capacity of a material for storage of strain energy in the elastic range (cm-kg/cm<sup>3</sup>). Thus the area under the unloading curve in Figure 20.2 is a measure of resilience of the material. As in the case of toughness, when a force-deformation curve is used, the size of the specimen and the loaded area should be specified.

### **Mechanical hysteresis**

The energy absorbed by a material in a cycle of loading and unloading evaluated as area between loading and unloading curve (Figure 20.2). Mechanical hysteresis is a measure of the; damping capacity or the ability of the material to dissipate the strain energy as heat (cm-kg per cycle).

### **Stressed object**

An object under a "balanced" set of forces, tending to change its shape or size, or both.

### **Strained object**

An object subjected to a change of shape or size, or both as a result of application of a "balanced" set of forces.

### **Elastic-fore-effect and elastic after-effect**

Delayed elastic deformations which take place upon loading and recovery upon unloading (Figure 20.2).

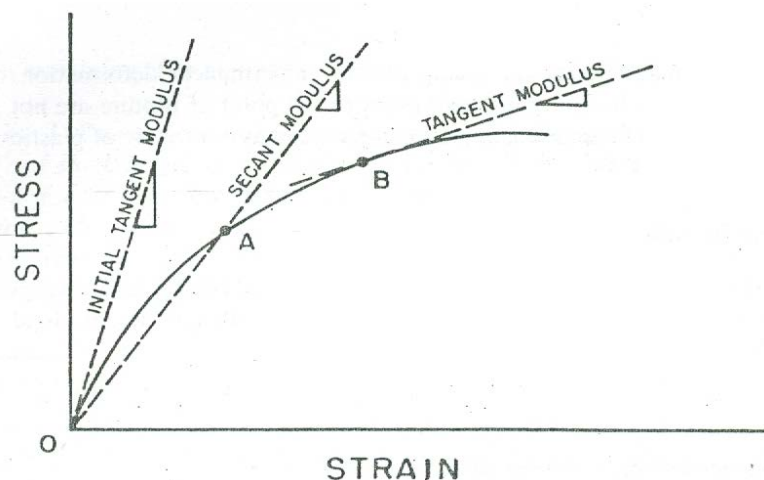


Figure 20.3 Methods for defining the modulus in non-linear stress-strain diagrams

### **Rigidity or shear modulus**

Rigidity or shear modulus is the ratio between shearing stress and the elastic shearing strain ( $\text{kg/cm}^2$ ).

### **Deviatoric stress component**

The stress which is responsible for change in shape.

### **Isotropic stress component**

The stress which is responsible for change in volume.

### **Viscoelasticity**

A combined solid-like and liquid-like behavior in which the stress-strain relationship is time dependent.

### **Linear viscoelasticity**

A viscoelastic behavior in which the ratio of stress to strain is a function of time alone and not of the stress magnitude.

### **Stress relaxation**

Decay of stress. with time when the material is suddenly deformed to a given deformation-constant strain.

### **Relaxation time**

The rate of stress decay in- a material subjected to a sudden strain. It is the time required for the stress in the Maxwell model, representing stress relaxation behavior, to decay to  $\frac{1}{e}$  or approximately 37 percent of its original value.

### **Creep**

Deformation with time when the material is suddenly subjected to a dead load-constant stress.

### **Retardation time**

The rate at which the retarded elastic deformation takes place in a material creeping under dead load. It is the time required for the Kelvin model, representing creep behavior, to deform to  $(1-\frac{1}{e})$  or about 63 percent of its total deformation.

### **Viscosity**

Resistance to flow indicated by coefficient of viscosity.

### **Viscosity coefficient**

The ratio of shearing stress to shearing rate in Newtonian fluids.

$$\left( \frac{\text{dynes} - \text{sec}}{\text{cm}^2} \right) = \text{poise or} \left( \frac{\text{lb} - \text{sec}}{\text{ft}^2} \right)$$

### **Kinematic viscosity**

Coefficient of viscosity divided by the mass density (ft<sup>2</sup>/sec).

### **Newtonian liquid**

An ideal fluid in which the relationship between shear stress and shear rate is a straight line passing through the origin (Figure 20.3).

### **Non-Newtonian liquid**

A liquid in which the relationship between shear stress and shear rate is non-linear. If the flow curve is concave to the shear stress axis, the flow is called

***dilatant***. If the flow curve is convex to the shear stress axis, the flow is called **pseudoplastic**.

**Thixotropic fluids**

Those fluids which show a decrease in shear stress with time of shear at a given shear rate.

**Rheopectic fluids**

Those fluids which show an increase in shear stress with time of shear at a given shear rate.

## LECTURE NO. 21

PHYSICAL STATES OF A MATERIAL, CLASSICAL IDEAL MATERIALS, IDEAL ELASTIC BEHAVIOR (HOOKEAN BODY), IDEAL PLASTIC BEHAVIOR (ST. VENANT BODY), IDEAL VISCOUS BEHAVIOR (NEWTONIAN LIQUID)

### PHYSICAL STATES OF A MATERIAL

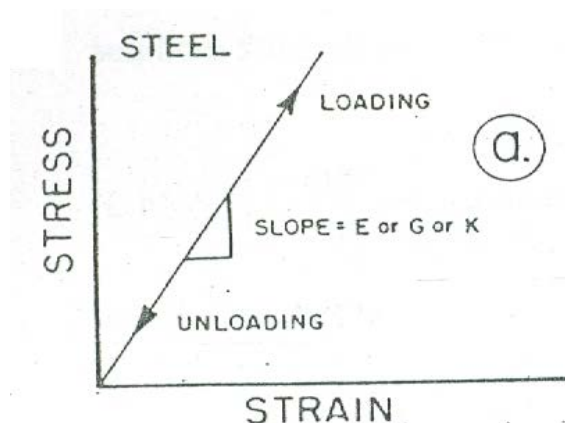
The state of various materials depends at any instant on load and deformation history to which it is subjected to as well as environmental factors such as temperature. In the case of biological materials, the moisture content also affects the physical state of the material. The **creep compliance function  $J(t)$**  is the ratio of shear strain to shear stress at any given time  $t$  when the load or stress is kept constant. The **relaxation modulus function  $G(t)$**  is the ratio of shear stress to shear strain at any time  $t$  when strain is kept constant.

$$\text{creep compliance function } J(t) = \frac{\text{Shear Strain}}{\text{Shear Stress}}$$

$$\text{relaxation modulus function } G(t) = \frac{1}{J(t)}$$

### CLASSICAL IDEAL MATERIALS

There are two types of deformation, elastic deformation and flow. Flow is also divided into plastic flow and viscous flow. Therefore, **elasticity**, **plasticity** and **viscosity** are **three fundamental properties** by which the rheological behavior of a material can be described. The three classical ideal bodies representing these properties are Hookean body, St. Venant body, and Newtonian liquid. *Since no real material behaves perfectly elastic or perfectly plastic, the three ideal bodies have been chosen to serve as standards of comparison in the analysis of the behavior of any real material.*





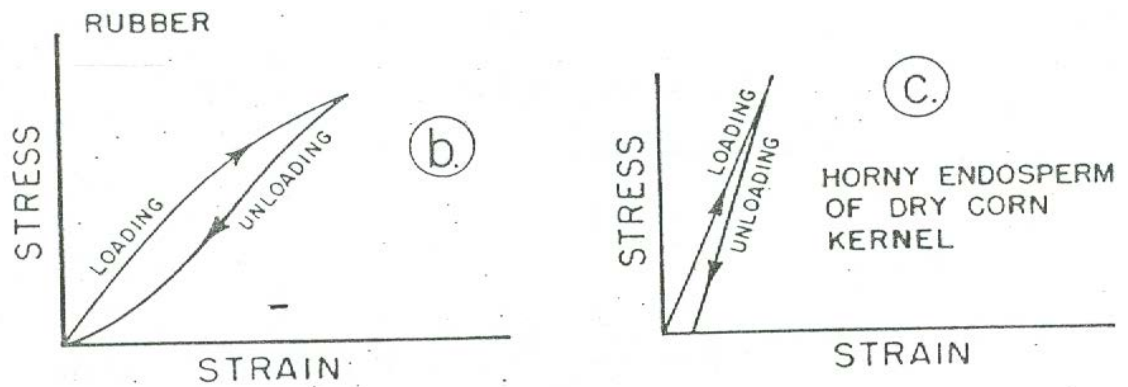


Figure 21.1 a) Linear elasticity in steel, (b) non-linear elasticity in rubber, (c) inelasticity in corn

### Ideal elastic behavior (Hookean body)

In a Hooke body, stress is directly proportional to strain as illustrated in Figure 21.1 (a). The relationship is known as the Hooke's law and the behavior is referred to as Hookean behavior. The difference between the Hookean or linear elasticity shown for steel and the non-linear elasticity shown for rubber is shown in the Figure 21.1 (b).

Compression tests of a variety of food and feed materials such as fruits and vegetables, forage, cereal grains, and egg shell have indicated that Hookean elasticity, even for very small strains, apparently does not exist in these biological materials. Figure 21.1 (c) shows the first cycle of loading and unloading for the horny endosperm of dry com kernel. This type of curve which shows some residual deformation upon unloading is typical for most of the food and feed materials.

Based on Hooke's law and together with Poisson's ratio, the following relationships have been established for elastic, homogeneous and isotropic materials (Figure 2).

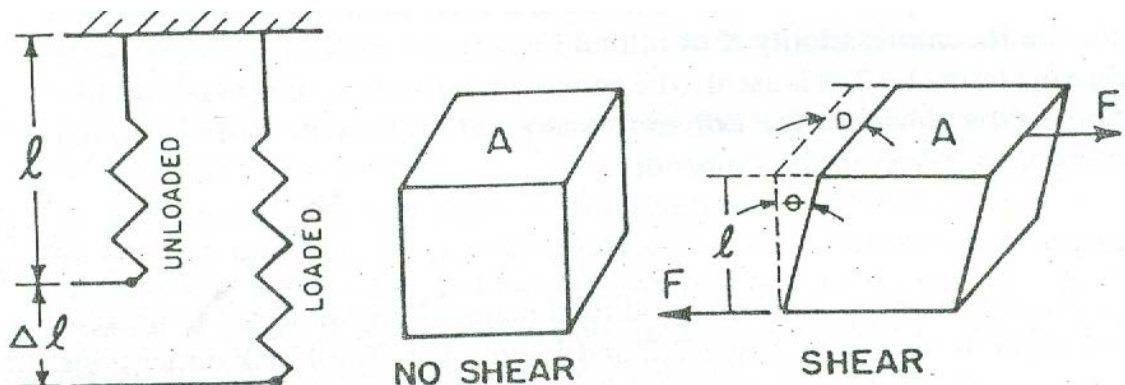


Figure 21.2. Hooke's elasticity in tension and shear

When the Hooke solid is under tensile or compressive stress, modulus of elasticity or Young's modulus is given by

$$E = \frac{\text{tensile or compressive stress } \sigma}{\text{tensile or compressive strain } \varepsilon} \text{ where } \varepsilon = \frac{\Delta l}{l}$$

When the Hooke solid is subjected to distortion by shear stresses the shear modulus or modulus of rigidity is given by

$$G = \frac{\text{shear stress } \tau}{\text{shear strain } \gamma} \text{ where } \gamma = \frac{D}{l} = \tan \theta$$

When the Hookean solid is under hydrostatic pressure the bulk modulus or incompressibility is given by

$$K = - \frac{\text{hydrostatic pressure } p}{\text{Volume strain } \varepsilon_v} \text{ where } \varepsilon_v = \frac{\Delta v}{v}$$

The relationship between the above elastic constants and Poisson's ratio  $\mu$  is given by

$$\frac{1}{E} = \frac{1}{3G} + \frac{1}{9K}$$

$$E = 3K(1 - 2\mu)$$

$$E = 2G(1 + \mu)$$

$$\mu = \frac{(3K - E)}{6K}$$

$$\mu = \frac{(E - 2G)}{2G}$$

For most materials Poisson's ratio is between 0.2 and 0.5. The Poisson's ratio approaches 0.5 as the character of a material approaches that of rubber or liquids. This becomes evident when we recall that a liquid cannot support any shear stresses, resulting in a rigidity modulus of  $G$  equals zero.

### **Ideal plastic behavior (St. Venant body)**

A friction block such as shown in Figure 21.3 can be used as the mechanical model for St. Venant Body representing ideal plasticity. In this model the solid friction between the block and the surface prevents any movement of the block. When the pull slightly exceeds the static friction, the block starts to move. Once the movement begins, the pull must overcome only the kinetic friction to keep the block moving. In this model the displacement gradient (cm/cm) stands for shearing strain  $\gamma$  in an ideal plastic material. The material

does not flow until a limiting value of shearing stress  $\tau_y$ , called the "yield-stress," is reached. The material can sustain no stress greater than this value and flows indefinitely under this stress unless distortion is restricted by some other factor.

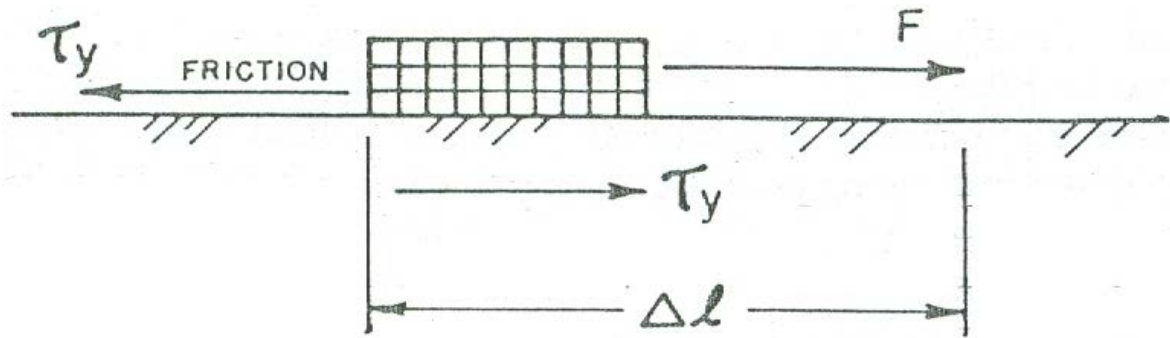


Figure 21.3 Friction block representing St. Venant Body for ideal plasticity

### **Ideal viscous behavior (Newtonian liquid)**

In an ideal plastic material, a minimum stress, called the yield stress, is necessary before deformation and flow begins. In a liquid, deformation and flow begin as soon as a shear stress is applied, and when the stress is removed, like in the case of plastic flow, it will not return to its original state. In a liquid, strain is a function not only of stress but of time as well.

In a "simple" liquid with laminar flow the velocity gradient may be expressed as follows:

$$\frac{dv}{dy} = \phi \tau = \frac{1}{\eta} \tau$$

where  $dv$  is the velocity increment of one layer of the liquid passing over another layer a distance  $dy$  apart (Figure 21.4). The movement is due to a shearing stress,  $\tau$ , which is proportional to the velocity gradient with proportional factor  $\phi$ , called fluidity, or  $\frac{1}{\phi} = \eta$ , called viscosity.

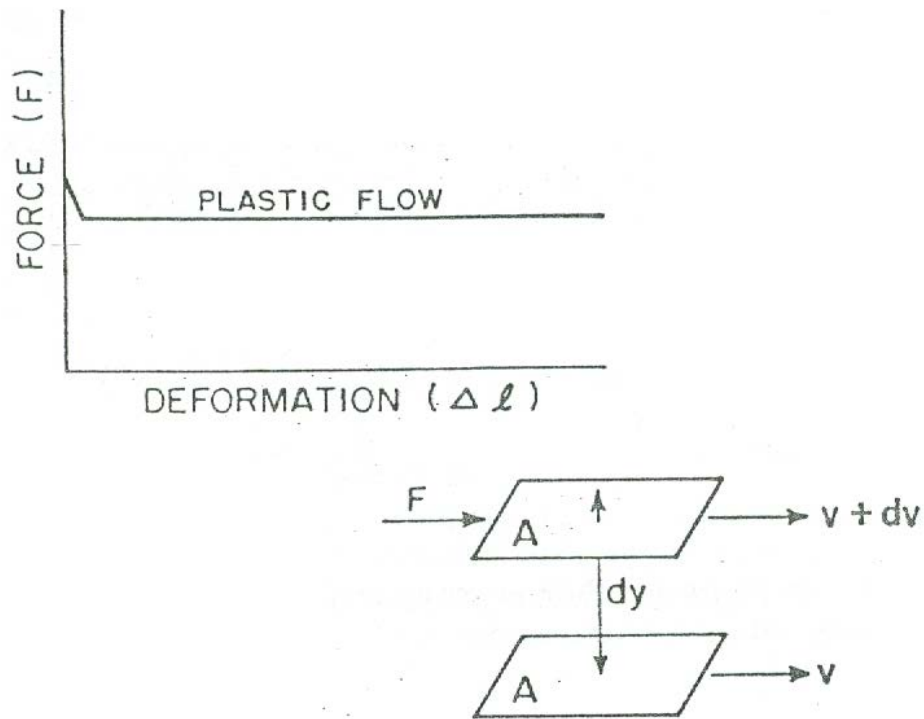


Figure 21.4 Laminar flow of a liquid under shear

Figure 21.5 shows the plot of Newton's law of viscosity and a simple **dashpot** representing the mechanical model for Newtonian liquids. The plot is a straight line passing through the origin. The slope of the line is by definition the viscosity. This shows that although the yield value in an ideal liquid is zero, there is an internal frictional resistance to flow called the viscosity. The mechanical model, called the viscous element, is supposed to be a weightless, loosely fitted piston moving in a medium filled with the liquid.

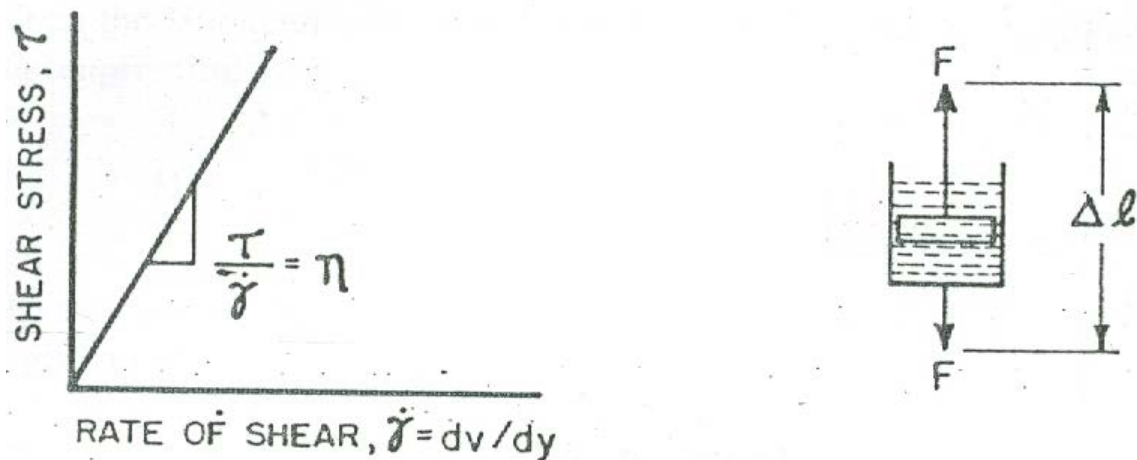


Figure 21.5 Newtonian liquid and the model

The viscosity of a liquid is measured by the tangential force and a unit area of either of two horizontal planes at unit distance apart, required to move one plane with unit velocity with reference to the other plane. When the force is

one dyne over one square centimeter, the distance between planes is one centimeter, and the velocity one centimeter per second, the absolute viscosity is by definition one "poise." A centipoise, which is one  $\frac{1}{100}$  of one poise, is usually taken as the unit of measurement. The kinematic viscosity or "stokes," used in engineering practice, is  $\frac{\eta}{\rho}$ , where  $\rho$  is the mass density of the liquid. The units of viscosity in the system are kg-sec/cm<sup>2</sup>.

## LECTURE NO. 22

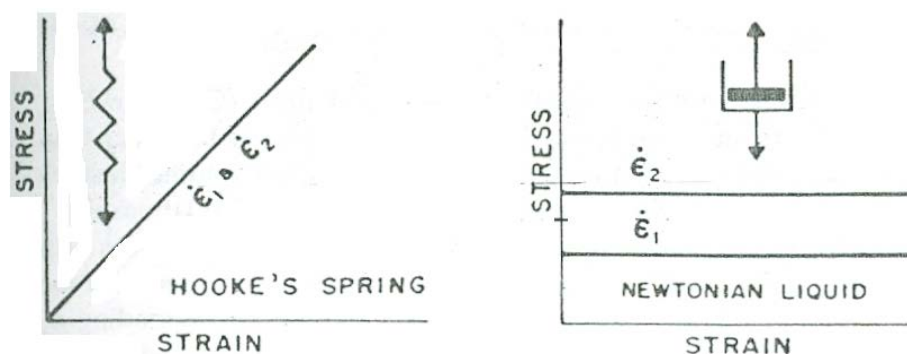
### RHEOLOGICAL MODELS, ELECTRICAL EQUIVALENCE OF MECHANICAL MODELS

#### Rheological Models

Mechanical models consisting of springs and dash pots are used to explain and interpret the rheological behavior of linear viscoelastic materials. The model is supposed to behave qualitatively, to some degree of approximation, in a manner similar to that of an actual material. If the mechanical behavior can be expressed in terms of force-deformation or stress-strain and time, the results can lead to a rheological equation. This equation can be used to explain and in certain cases predict the behavior of the material under various loading conditions.

The two basic mechanical elements used in mechanical models are a spring which obeys Hooke's law and a dashpot with a Newtonian liquid. These elements and their two basic combinations, **Kelvin model** and **Maxwell model**, are shown in Figure 22.1. These curves are drawn for two strain rates  $\dot{\epsilon}_1$  and  $\dot{\epsilon}_2$ . It is shown that for the spring the behavior is independent of time. For the dashpot and the other models containing a dashpot, stress - strain relationship is time dependent.

In the **Kelvin model**, both the spring and dashpot are forced to move together at a constant rate. Therefore, the force due to the dashpot jumps to a constant value instantaneously and remains constant while the force on the spring starts at zero and gradually builds up. When the effects of the two elements are superimposed the net effect is the behavior of the Kelvin model.



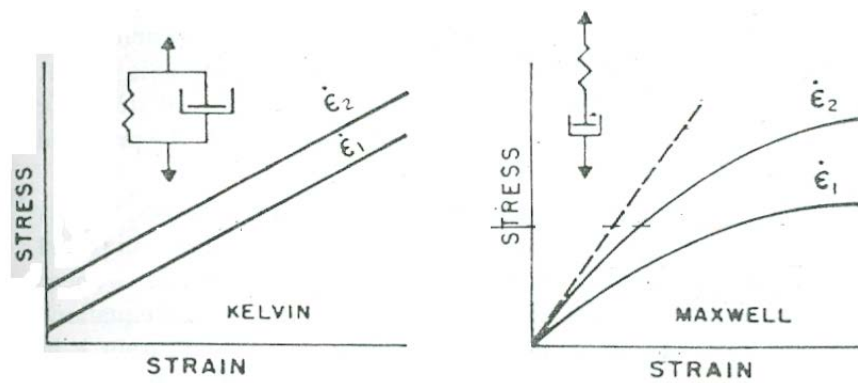


Figure 22.1 Effect of strain rate  $\dot{\epsilon}$  on stress-strain curves of four basic

models  $\dot{\epsilon}_2 = 2\dot{\epsilon}_1$

In the Maxwell model, initially all the stress goes into stretching the spring, resulting in an initial straight line portion of the curves which obeys Hooke's law. As the spring changes, the dashpot carries more and more of the stress until the spring reaches the end of its elongation. At this point all the stress goes into flow in the dashpot and the stress-strain curve levels off.

### Electrical equivalence of mechanical models

It has been said that if a physical phenomenon can be represented by a mechanical model, it can also be represented by an infinite number of other models. Since the differential equations governing the mechanical behavior of a material provides the most complete knowledge of its properties, and the most thoroughly studied examples of these equations are available for the linear electrical networks, the electrical analog of the mechanical models has been suggested for rheological studies.

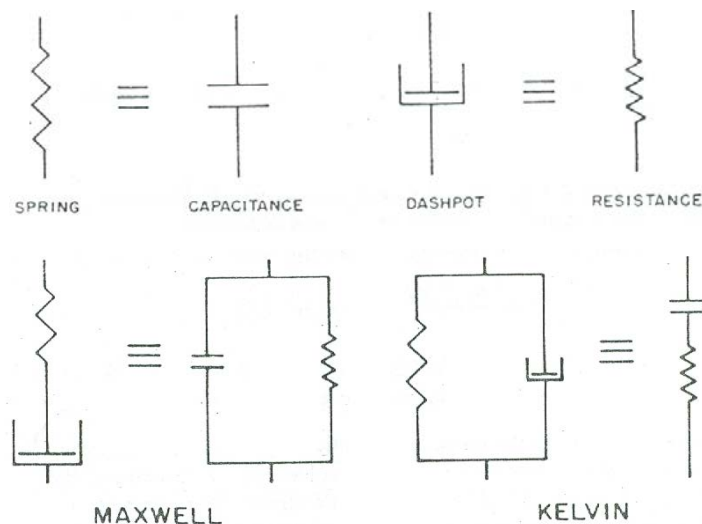


Figure 22.2 Electrical analogs of mechanical models

In this analogy, the spring, representing elasticity, is replaced by a capacitance and the dashpot, representing viscosity, is replaced by a resistance. The tension and compression of the spring corresponds to charging and discharging of the capacitor. The work done on the dashpot is dissipated as heat just as the work done on the electrical resistance is converted to heat. Figure 22.2 shows the electrical analog of the basic mechanical element and the models. Note that when elements are coupled in parallel in the mechanical model, its equivalent in the electrical network is a series coupling. Similarly, a series coupling in the mechanical system has a parallel equivalence in the electrical system. In the electrical network, the stress is represented by the electric potential (voltage) and the strain by electric current.



## LECTURE NO. 23

### RHEOLOGICAL EQUATIONS

#### **Total stress and total strain**

When a material is subjected to tensile or compressive stresses resulting in both change in shape and change in volume, the deformation may be shown to be a combination of both shear and bulk deformation. Consequently, stress components at any point of this material can be decomposed into a deviatoric stress component, which is responsible for the change in shape, and an isotropic stress component which is responsible for the change in volume. Therefore, the total stress in the x direction,  $\sigma_x$  can be written as follows:

$$\sigma_x = S_x + \bar{\sigma}$$

Where  $S_x$  is the deviatoric stress and  $\bar{\sigma}$  is the mean normal stress defined as

$$\bar{\sigma} = \frac{1}{3}(\sigma_x + \sigma_y + \sigma_z)$$

Similarly, the total strain in the x direction,  $\epsilon_x$ , can be resolved into a deviatoric strain  $e_x$  and a mean normal strain  $\bar{\epsilon}$  as follows:

$$\epsilon_x = e_x + \bar{\epsilon}$$

where

$$\bar{\epsilon} = \frac{1}{3}(\epsilon_x + \epsilon_y + \epsilon_z)$$

## LECTURE NO. 24

### AERO AND HYDRODYNAMIC PROPERTIES, DRAG COEFFICIENT AND TERMINAL VELOCITY

#### Aero and Hydrodynamic Characteristics

In handling and processing of agricultural products often air or water is used as a carrier for transport or for separating the desirable product from the unwanted materials. The pneumatic separation and conveying has been in use in agricultural machinery and food processing equipment for many years. Use of water however, as a carrier for more economical transport or less injury to such products as fruits and vegetables, is a relatively new idea in the agricultural industry. In either case, fluid flow occurs around the solids and the problem involves the action of the forces exerted by the fluid on these solids. As the principles of this subject, known as fluid mechanics, find increasingly wide applications in handling and processing of agricultural products, it becomes necessary to have a knowledge of those physical properties which affect the aero and hydrodynamic behavior of agricultural products.

#### DRAG COEFFICIENT

When fluid flow occurs about immersed objects, the action of the forces involved can be illustrated by diagram as shown in Figure 24.1. The pressure on the upper side of the object is less than and that on the lower side is greater than the pressure  $P$  in the undisturbed fluid stream. This results in a decrease of pressure,  $-P$ , on the upper side, and an increase of pressure,  $+P$ . In addition to these forces normal to the surface of the object, there are shear stresses,  $\tau$ , acting tangential to the surface in the direction of flow and resulting from frictional effects.

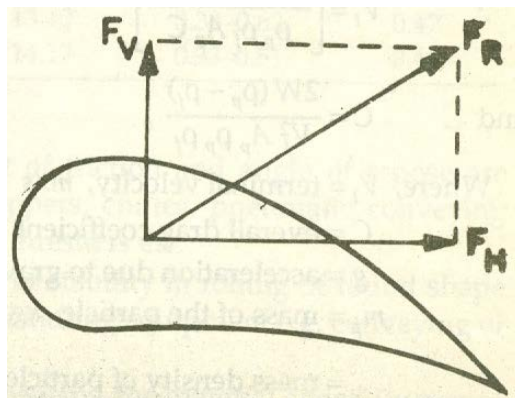


Figure 24.1 The Forces acting on a body immersed in a fluid current

The resultant force  $F_r$  may be resolved into components,  $F_h$ , the drag and  $F_L$  the lift. The equations for calculating drag and lift have been derived by dimensional analysis assuming the smooth object having a projected area,  $A_p$ , moving through a fluid of mass density, ' $\rho_f$ ', viscosity,  $\eta$ , and modulus of elasticity,  $E$ , with a velocity,  $V$ . Therefore,

$$F_h = f_1(A_p, \rho_f, \eta, E, V)$$

$$F_L = f_2(A_p, \rho_f, \eta, E, V)$$

Employing the methods of dimensional analysis, the following equations have been established for drag and lift

$$F_h = C_D A_p \frac{\rho_f V^2}{2}$$

$$F_L = C_L A_p \frac{\rho_f V^2}{2}$$

where  $C_D$  and  $C_L$  are the (dimensionless) drag coefficient and lift coefficient of the object, respectively.

In most agricultural engineering applications the moving object is usually free to assume its own random orientation. For this reason the net resistance force  $F_r$  can be given in terms of an overall drag coefficient  $C$  as follows

$$F_r = \frac{1}{2} C A_p \rho_f V^2$$

where

$F_r$  = resistance drag force or weight of particle at terminal velocity, kg

$C$  = overall drag coefficient (dimensionless)

$A_p$  = projected area of the particle normal to direction of motion,  $m^2$

$\rho_f$  = mass density of the fluid,  $kg.s^2 / m^4$

$V$  = relative velocity between main body of fluid and object, m/s

### **Terminal velocity**

The **terminal velocity** of a particle may be defined as equal to the air velocity at which a particle remains in suspended state in a vertical pipe. In the condition of free fall, the particle attains a constant terminal velocity,  $V_t$ , the net gravitational accelerating force,  $F_g$ , equals the resisting upward drag force,  $F_r$ .

$$\text{If } V=V_t, F_g = F_r$$

By substituting the values of  $F_g$  and  $F_r$ , the terminal velocity can be expressed as;

$$m_p g \left[ \frac{(\rho_p - \rho_f)}{\rho_p} \right] = \frac{1}{2} C A_p \rho_f V_t^2$$

$$V_t = \left[ \frac{2W(\rho_p - \rho_f)}{\rho_p \rho_f A_p C} \right]^{\frac{1}{2}}$$

$$\text{and } C = \frac{2W(\rho_p - \rho_f)}{V_t^2 A_p \rho_p \rho_f}$$

where,

$V_t$  = terminal velocity,  $m / s$

$C$  = overall drag coefficient

$g$  = acceleration due to gravity,  $mls^2$

$m_p$  = mass of the particle,  $kg$

$\rho_p$  = mass density of particle,  $kg.s^2/m^4$

$\rho_f$  = mass density of fluid,  $kg.s^2/m^4$

$A_p$  = projected area of particle in perpendicular direction of motion,  $m^2$

$W$  = weight of particle,  $kg$

In the steady state conditions, after attaining the terminal velocity, if the density of the particle is greater than the density of the fluid, the particle will move downward. If the density of the particle is lesser than the density of the fluid, the particle will rise upward. If the separation of mixture of wheat and foreign matters is to be achieved by air stream, the terminal velocities of each component of mixture decide the range of air velocity to be used for a definite extent of separation. . The drag coefficient of the material and its resistance to air flow depend upon, (1) the bed thickness of the material, (2) type, shape and size of grain, (3) the air velocity and (4) orientation and packing of the material.

## LECTURE NO. 25

### EVAPORATION, BOILING POINT ELEVATION, TYPES OF EVAPORATORS, BATCH TYPE PAN EVAPORATOR, NATURAL CIRCULATION EVAPORATORS

#### Evaporation

Evaporation is an important unit operation commonly employed to remove water from dilute liquid foods to obtain concentrated liquid products. Removal of water from foods provides microbiological stability and assists in reducing transportation and storage costs. A typical example of the evaporation process is in the manufacture of tomato paste, usually around 35-37% total solids obtained by evaporating water from tomato juice, which has an initial concentration of 5-6 % total solids.

Evaporation differs from dehydration, since the final product of the evaporation process remains in liquid state. It also differs from distillation, since the vapors produced in the evaporator are not further divided into fractions. In Fig. 25.1 a simplified schematic of an evaporator is shown.

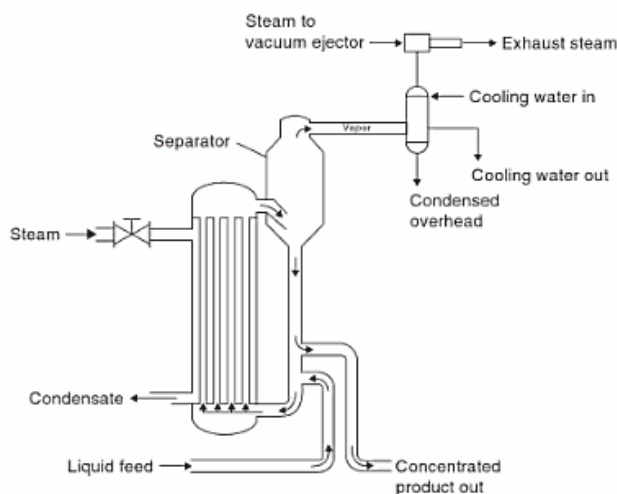


Fig. 25.1 Single effect evaporator

Essentially, an evaporator consists of a heat exchanger enclosed in a large chamber; a non contact heat exchanger provides the means to transfer heat from low-pressure steam to the product. The product inside the evaporation chamber is kept under vacuum. The presence of vacuum causes the temperature difference between steam and product to increase and the product boils at relatively low temperatures, thus minimizing heat damage. The vapors produced are conveyed through a condenser to a vacuum system. The steam condenses inside the heat exchanger and the condensate is discarded.

In the evaporator shown in Fig. 25.1, the *vapors produced are discarded without further utilizing their inherent heat*, therefore this type of evaporator is called a **single-effect evaporator**, since the vapors produced are discarded. If the vapors are reused as the heating medium in another evaporator chamber, as shown in Fig.25.2. the evaporator system is called a **multiple-effect evaporator**.

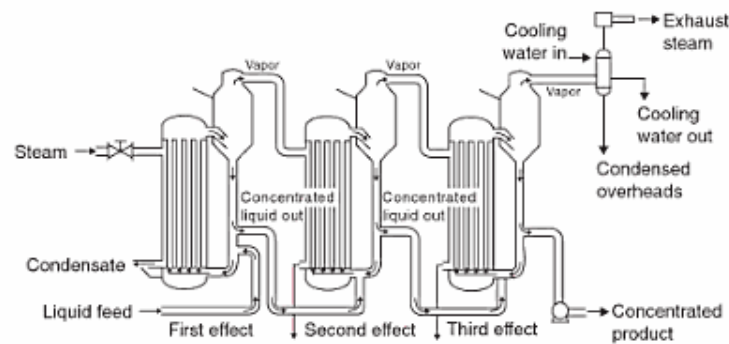


Fig. 25.2 Multiple (triple) -effect evaporator

In a multi-effect evaporator, steam is used only in the first effect. The use of vapors as a heating medium in additional effects results in obtaining higher energy-use efficiency from the system. The partially concentrated product leaving the first effect is introduced as feed into the second effect. After additional concentration, product from the second effect becomes feed for the third effect. The product from the third effect leaves at the desired concentration. This particular arrangement is called a **forward feed system**. Other flow arrangements used in industrial practice include **backward feed systems** and **parallel feed systems**.

The characteristics of the liquid food have a profound effect on the performance of the evaporation process. As water is removed the liquid becomes increasingly concentrated, resulting in reduced heat transfer. The boiling point rises as the liquid concentrates resulting in a smaller differential of temperature between the heating medium and the product. This causes reduced rate of heat transfer.

Food products are noted for their heat sensitivity. Evaporation processes must involve reducing the temperature for boiling as well as the time of heating, to avoid excessive product degradation.

## **Boiling-Point Elevation**

Boiling-point elevation of a solution (liquid food) is defined as the increase in boiling point over that of pure water, at a given pressure.

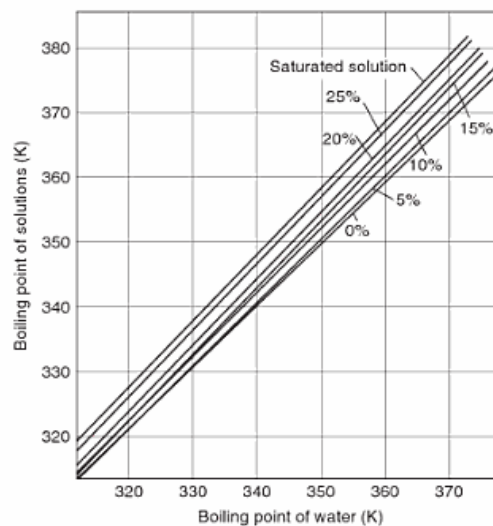


Fig. 25.3 Dühring lines illustrating the influence of solute concentration on boiling point elevation

A simple method to estimate boiling-point elevation is the use of Dühring's rule. The Dühring rule states that a linear relationship exists between the boiling-point temperature of the solution and the boiling-point temperature of water at the same pressure. Dühring lines for a sodium chloride-water system are shown in Fig.25.3.

## **Types of Evaporators**

Several types of evaporators are used in the food industry.

### **1. Batch-Type Pan Evaporator**

One of the simplest types of evaporators used in the food industry is the batch-type pan evaporator, shown in Fig.25.4. The product is heated in a steam jacketed spherical vessel. The heating vessel may be open to the atmosphere or connected to a condenser and vacuum. Vacuum permits boiling the product at temperatures lower than the boiling point at atmospheric pressure, thus reducing the thermal damage to heat sensitive products.

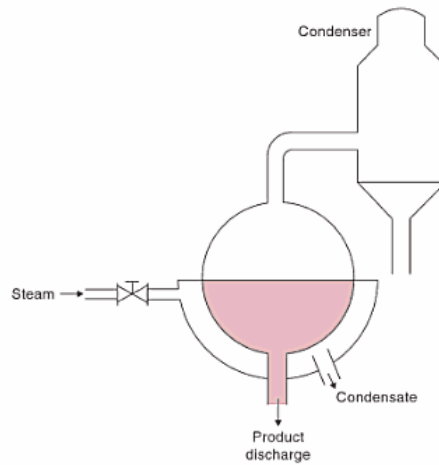


Fig. 25.4 A batch-type pan evaporator

The heat-transfer area per unit volume in a pan evaporator is small. Thus, the residence time of the product is usually very long. Heating of the product occurs mainly due to **natural convection**, resulting in smaller convective heat transfer coefficients. The poor heat transfer characteristics substantially reduce the processing capacities of the batch-type pan evaporators.

## 2. Natural Circulation Evaporators

In natural circulation evaporators, short vertical tubes, typically **1- 2 m long** and **50- 100 mm in diameter**, are arranged inside the steam chest. The whole calandria (tubes and steam chest) is located in the bottom of the vessel. The product, when heated, rises through these tubes by natural circulation while **steam condenses outside the tubes. Evaporation takes place inside the tubes**, and the product is concentrated. The concentrated liquid falls back to the base of the vessel through a central annular section. A natural circulation evaporator is shown in Fig.25.5.

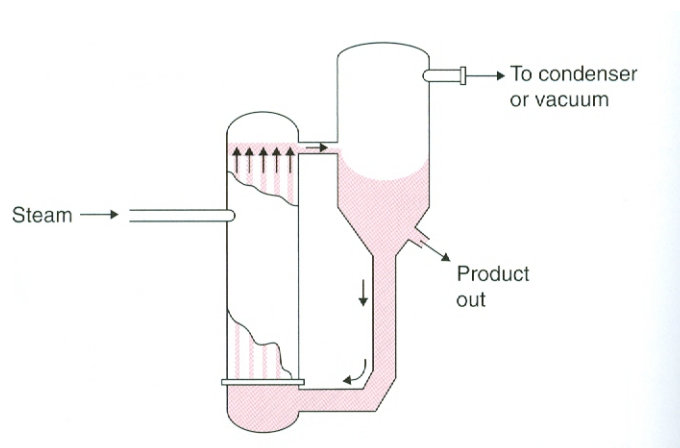


Fig.25.5 A natural circulation evaporator



## LECTURE NO. 26

### RISING FILM EVAPORATOR, FALLING FILM EVAPORATOR, RISING AND FALLING FILM EVAPORATOR, FORCED-CIRCULATION EVAPORATOR PLATE EVAPORATOR

#### 1. Rising-Film Evaporator

In a rising-film evaporator (Fig. 26.1), a low-viscosity liquid food is allowed to boil inside 10-15 m long vertical tubes. The tubes are heated from the outside with steam. The liquid rises inside these tubes by vapors formed near the bottom of the heating tubes. The upward movement of vapors causes a thin liquid film to move rapidly upward. A temperature differential of at least **14°C** between the product and the heating medium is necessary to obtain a well developed film. High convective heat-transfer coefficients are achieved in these evaporators. Liquid can be recirculated if necessary to obtain the required solid concentration.

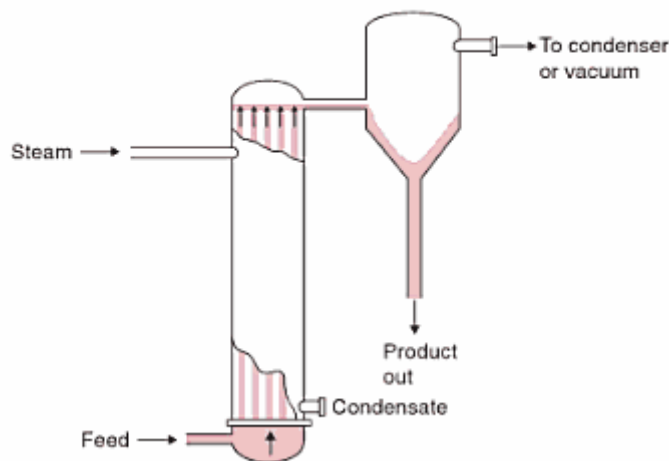


Fig. 26.1 a rising-film evaporator

#### 2 Falling-Film Evaporator

In contrast to the rising-film evaporator, the falling-film evaporator has a thin liquid film moving downward under gravity on the inside of the vertical tubes. (Fig.26.2). The design of such evaporators is complicated by the fact that distribution of liquid in a uniform film flowing downward in a tube is more difficult to obtain than an upward flow system such as in a rising-film evaporator. This is accomplished by the use of specially designed distributors or spray nozzles.

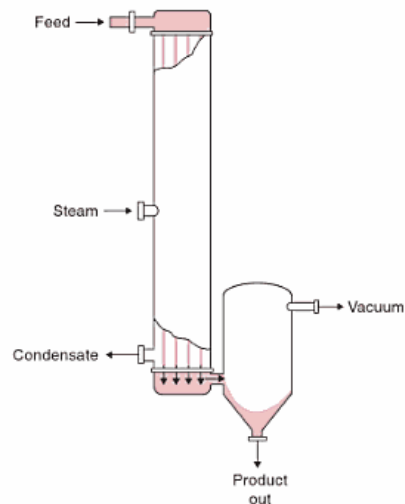


Fig. 26.2 Falling-film evaporator

The falling-film evaporator allows a greater number of effects than the rising-film evaporator. For example, if steam is available at 110 °C and the boiling temperature in the last effect is 50°C, then the total available temperature differential is 60°C. Since rising-film evaporators require 14°C temperature differential across the heating surface, only four effects are feasible. However, as many as 10 or more effects may be possible using a falling-film evaporator. The falling-film evaporator can handle more viscous liquids than the rising-film type. This type of evaporator is best suited for highly heat-sensitive products such as orange juice. Typical residence time in a falling-film evaporator is 20-30 seconds, compared with a residence time of 3-4 minutes in a rising-film evaporator.

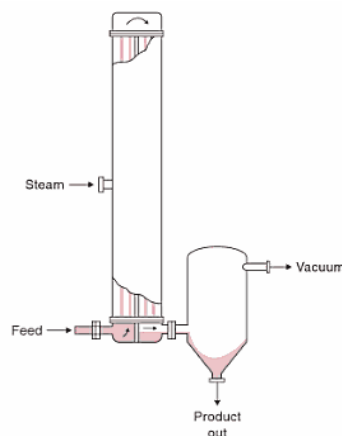


Fig.26.3 Rising / falling-film evaporator

### 3. Rising/Falling-Film Evaporator

In the rising/falling-film evaporator the product is concentrated by circulation through a rising-film section followed by a falling-film section of the evaporator. As shown in Fig.26.3, the product is first concentrated as it ascends

through a rising tube section, followed by the pre-concentrated product descending through a falling-film section; there it attains its final concentration.

#### 4 Forced-Circulation Evaporator

The forced-circulation evaporator involves a non-contact heat exchanger where **liquid food is circulated** at high rates (Fig. 26.4). A hydrostatic head, above the top of the tubes, eliminates any boiling of the liquid. Inside the separator, absolute pressure is kept slightly lower than that in the tube bundle. Thus, the liquid entering the separator flashes to form a vapor. The temperature difference across the heating surface in the heat exchanger is usually 3-5°C. **Axial flow pumps** are generally used to **maintain high circulation rates** with **linear velocities of 2- 6 m/s**, compared with a linear velocity of **0.3-1 m/s** in **natural-circulation evaporators**. Both capital and operating costs of these evaporators are very low in comparison with other types of evaporators.

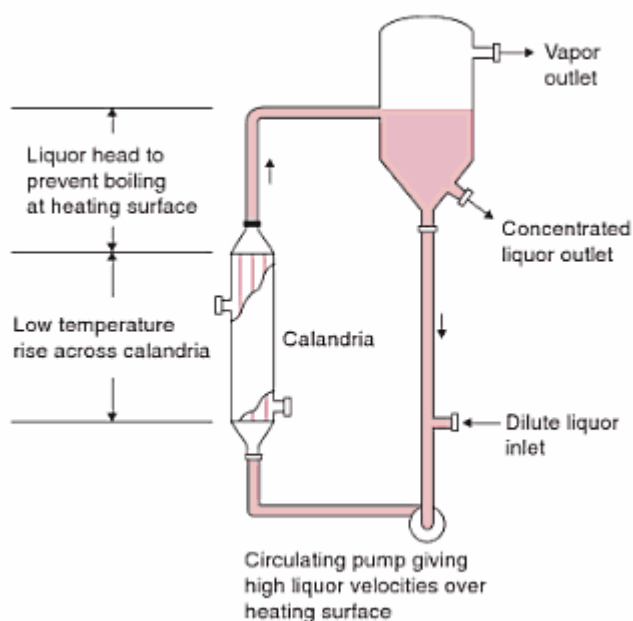


Fig. 26.4 A forced-circulation evaporator

#### 5. Plate evaporators

In addition to the tubular shape, **plate evaporators** are also used in the industry. Plate evaporators use the principles of rising falling-film, falling-film, wiped-film, and forced-circulation evaporators. The plate configuration often provides features that make it more acceptable.

A **rising/falling-film plate** evaporator is more compact, thus requiring less floor area than a tubular unit.

## LECTURE NO. 27

DESIGN OF A SINGLE EFFECT EVAPORATOR, MATERIAL AND ENERGY BALANCES, EVAPORATOR EFFICIENCY, BOILING POINT ELEVATION, METHODS OF IMPROVING EVAPORATOR EFFICIENCY

### Design of a Single Effect Evaporator

The primary quantities required to design an evaporator are the flow rates of the major streams: feed, vapour and concentrated liquor; the steam flow rate and the area of the heat transfer surface across which heat is transferred from steam to liquid in the evaporator. This requires a **material balance**, an **enthalpy balance** and a **heat transfer rate equation** to be solved simultaneously.

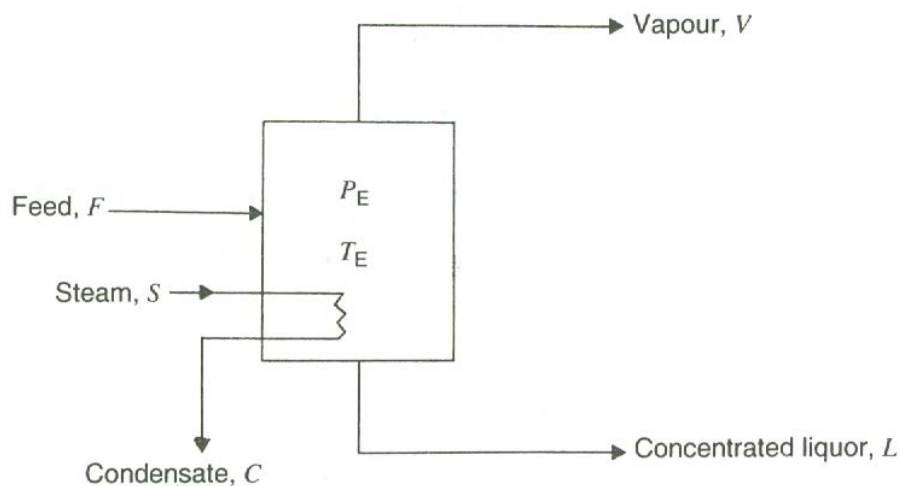


Fig. 27.1 Single effect evaporator: Material and energy balance

### Material and Energy Balances

Referring to Figure 27.1, an overall material balance across a single effect evaporator yields

$$F = V + L \quad \text{-----} (27.1)$$

where  $F$ ,  $V$ , and  $L$  are the mass flow rates of feed, vapour, and liquor, respectively. The component material balance is now

$$x_F F = yV + x_L L \quad \text{-----} (27.2)$$

where  $x_F$ ,  $y$ , and  $x_L$  are the mass fractions of solids in the feed, vapour and liquor, respectively. However, because there is no solids in the vapour stream,  $y = 0$  and the component balance reduces to

$$x_F F = x_L L \quad \text{-----} (27.3)$$

An enthalpy balance over the evaporator involves two further streams, the **inlet steam S** and the **condensate C**. The combined enthalpy of the feed and

the steam must balance that of the vapour, liquor and condensate. Thus, if  $h_F$  is the specific enthalpy of the feed,  $h_S$  that of the steam and so on,

$$Fh_F + Sh_S = Vh_v + Lh_L + Sh_c \text{ ----- (27.4)}$$

where each term in Equation (4) represents a flow of heat associated with that particular stream and has units of either W or kW if  $h$  has units of  $\text{J.kg}^{-1}$  or  $\text{kJ.kg}^{-1}$ , respectively. Strictly, the steam and condensate should be included in the material balances. However they may be omitted because, of course, the flow rate and composition of the steam remains unchanged as it gives up heat and condenses. Thus, in Equation (12.4),  $S = C$ . For the purpose of calculation, the enthalpies of liquid streams are obtained from steam tables and care must be taken not to confuse the subscripts F and f.

Rearranging Equation (27.4) to give the steam flow rate produces

$$S(h_s - h_c) = Vh_v + Lh_L - Fh_F \text{ -----(27.5)}$$

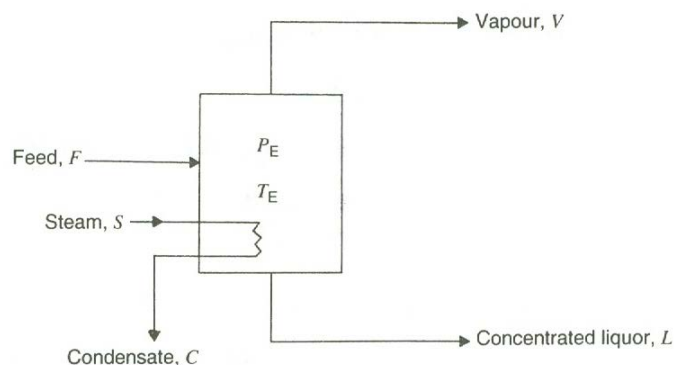


Fig.27.2 Single effect evaporator: material and enthalpy balance

Now the left-hand side of Equation (27.5), the difference between the enthalpy of the steam and that of the condensate, must be equal to the rate  $Q$  at which heat is transferred from the steam to the feed, that is,

$$Q = S(h_s - h_c) \text{ -----(27.6)}$$

The enthalpy given up by the steam is transferred across the tube walls of the calandria, across which the temperature difference is  $\Delta T$ , and therefore

$$S(h_s - h_c) = U A \Delta T \text{ -----(27.7)}$$

where  $A$  is the heat transfer surface area; this area must be determined in order for the calandria and the evaporator to be sized. An evaporator of course is a kind of heat exchanger and the overall heat transfer coefficient can be obtained by summing the various thermal resistances as in the examples of chapter seven. The temperature driving force is that between the steam and the boiling liquor in the evaporator. Hence

$$\Delta T = T_s - T_e \text{ -----(27.8)}$$

Any evaporator problem now requires the simultaneous solution of Equations (27.3), (27.5), and (27.7). However it is very likely that there will be sufficient information available to solve the material balance independently. Equally, if the working pressures of the evaporator are specified then the steam and condensate enthalpies can be determined from steam tables. The major difficulty may be in finding values of enthalpy and boiling point for food solutions, but a reasonable first estimate is to assume that the properties of food solutions approximate to those of water.

### Example 27.1

A single effect evaporator is to be used to concentrate a food solution containing 15% (by mass) dissolved solids to 50% solids. The feed stream enters the evaporator at 291 K with a feed rate of  $1.0 \text{ kg s}^{-1}$ . Steam is available at a pressure of 2.4 bar and an absolute pressure of 0.07 bar is maintained in the evaporator. Assuming that the properties of the solution are the same as those of water, and taking the overall heat transfer coefficient to be  $2,300 \text{ W m}^{-2} \text{ K}^{-1}$ , calculate the rate of steam consumption and the necessary heat transfer surface area.

Working in units of  $\text{kg s}^{-1}$ , the overall material balance becomes

$$1.0 = V + L$$

Substituting into the component material balance for  $x_F = 0.15$  and  $x_L = 0.50$  gives

$$0.15 \times 1.0 = 0.50 L$$

from which the unknown liquor flow rate is

$$L = 0.3 \text{ kg s}^{-1}$$

Hence from the overall balance the flow rate of vapour is

$$V = 0.7 \text{ kg s}^{-1}$$

To proceed with an enthalpy balance, specific enthalpies must be obtained from steam tables. If the steam and condensate remain saturated at 2.40 bar then  $h_s$  is equal to  $h_g$  at 2.40 bar and  $h_c$  is equal to  $h_f$  at 2.40 bar. Thus  $h_s = 2,715 \text{ kJ kg}^{-1}$  and  $h_c = 530 \text{ kJ kg}^{-1}$ . The feed enthalpy is determined by its temperature. Assuming the feed to be pure water,  $h_F$  is equal to  $h_f$  at 291 K and

therefore  $h_f = 75.5 \text{ kJ kg}^{-1}$ . The enthalpies of the vapour and liquor streams are a function of the pressure within the evaporator:  $h_v = 2,572 \text{ kJ kg}^{-1}$  ( $h_g$  at 0.07 bar) and  $h_L = 163 \text{ kJ kg}^{-1}$  ( $h_f$  at 0.07 bar). The enthalpy balance [Equation (5)] now becomes

$$S (2715 - 530) = (0.70 \times 2572) + (0.30 \times 163) - (1.0 \times 75.5)$$

from which  $S = 0.812 \text{ kgs}^{-1}$ . The rate of heat transfer, from Equation (6), is now

$$Q = 0.812 (2715 - 530) \text{ kW or } Q = 1774 \text{ kW}$$

The temperature of steam at 2.4 bar is  $T_s = 126.1 \text{ }^\circ\text{C}$  and the temperature of saturated liquid water at the evaporator pressure of 0.07 bar is  $T_E = 39.0 \text{ }^\circ\text{C}$ . Thus to find the heat transfer area from the rate equation,

$$A = \frac{Q}{U (T_s - T_E)}, \quad A = \frac{1774}{2.30 (126.1 - 39.0)} \text{ m}^2$$

or

$$A = 8.86 \text{ m}^2$$

### Evaporator Efficiency

A common measure of the efficiency of an evaporator is the mass of vapour generated per unit mass of steam admitted to the calandria. This quantity is known as the economy. Thus

$$\text{economy} = \frac{V}{S} \quad \text{-----}(27.9)$$

Clearly it is impossible, in a single effect evaporator, for 1 kg of steam to generate more than 1 kg of vapour. In practice, because of energy losses, the economy will be below unity and values of 0.8 or slightly greater may be expected for industrial units.

### Example 27.2

Calculate the economy of the evaporator in Example 27.1.

From the definition in Equation (27.9)

$$\text{economy} = \frac{0.70}{0.812}, \quad \text{economy} = 0.862$$

In other words 0.862 kg of vapour are produced for every kg of steam used.

### Example 27.3

An aqueous food solution at a temperature of 18 °C contains 6% solids by mass and is to be concentrated to 24 % solids in a single effect evaporator. The evaporator has a total heat transfer surface area of 30 m<sup>2</sup>, uses steam at 300 kPa and operates under a vacuum of 79.3 kPa. Previous operating experience with these conditions suggests an overall heat transfer coefficient of 2,200 W m<sup>-2</sup>K<sup>-1</sup>. Determine the mass flow rate of steam required and the evaporator economy.

The various specific enthalpies and temperatures are obtained from steam tables as follows:

For the steam and condensate at 300 kPa,  $h_s = 2,725 \text{ kJ kg}^{-1}$ ,  $h_c = 561 \text{ kJ kg}^{-1}$  and the steam temperature is 133.5°C. The enthalpy of feed at a temperature of 18 °C is  $h_F = 75.5 \text{ kJ kg}^{-1}$ . Taking atmospheric pressure to be 101.3 kPa, the pressure within the evaporator is 22.0 kPa and therefore the evaporator temperature (assuming no boiling point elevation) is 62.2 °C. Consequently  $h_v = 2,613 \text{ kJ kg}^{-1}$  ( $h_g$  at 0.22 bar) and  $h_L = 260 \text{ kJ kg}^{-1}$  ( $h_f$  at 0.22 bar).

From Equation (7) the steam flow rate is

$$S = \frac{U A \Delta T}{(h_s - h_c)}, \quad S = \frac{2.20 \times 30 \times (133.5 - 62.2)}{(2725 - 561)}$$

or

$$S = 2.175 \text{ kg s}^{-1}$$

Because neither the feed flow rate nor the product flow rate is specified, the material and energy balances must be solved simultaneously. The component balance, with  $X_F = 0.06$  and  $X_L = 0.24$ , is

$$0.06 F = 0.24 L$$

from which

$$F = 4L$$

Substituting this into the enthalpy balance gives

$$S(h_s - h_c) = (4L - L)h_v + L h_L - 4L h_F$$

and

$$2.175(2725 - 561) = (3L \times 2613) + 260 L - 302 L$$



This can be solved to give  $L = 0.604 \text{ kg s}^{-1}$  and from the overall material balance therefore  $V = 1.811 \text{ kg s}^{-1}$ . Consequently the economy becomes

$$economy = \frac{1.811}{2.175} \quad economy = 0.833$$

### Boiling Point Elevation

The vapour pressure of an aqueous solution is less than that of pure water. Consequently the boiling point of the solution is higher than that of pure water and this difference must be taken into account in the enthalpy balance. The boiling point rise or boiling point elevation is defined as the difference between the boiling point of the solution and that of pure water, at the same pressure.

### METHODS OF IMPROVING EVAPORATOR EFFICIENCY

In single stage evaporation the enthalpy of the vapour is wasted because the vapour is either vented to atmosphere or condensed. This poor use of steam results in low thermal efficiency and a low steam economy. Reusing the vapour, either by recycling it to the calandria or by passing it to the calandria of a second evaporator, means that 1 kg of original steam can be used to generate more than 1 kg of vapour giving economies greater than unity.

#### Vapour Recompression

**(a) Mechanical recompression** Mechanical recompression (Figure 27.3(a)) of the exhaust vapour from an evaporator allows the enthalpy of the vapour to be reused. In compressing the vapour its enthalpy is increased to that of the original steam. Because of inevitable heat losses in the system some make-up steam will be required but a large increase in economy can be expected. A major disadvantage of this technique is that a large volume of vapour must be handled which in turn requires a large compressor; positive displacement compressors are normally used. The increase in steam economy must be balanced against the running costs of the compressor.

**(b) Steam jet ejector:** An alternative method of reusing the vapour is to inject high pressure steam via a nozzle, or steam jet ejector (Figure 27.3 (b)). This creates a vacuum which entrains the low pressure vapour from the evaporator at right angles. The combined stream is then recycled to the calandria. Again, the fresh steam requirement is reduced but there are several advantages over mechanical recompression. The steam jet ejector has the ability to handle very large volumes of vapour and can operate at lower

pressures. There are no moving parts, no power requirement and corrosion resistant materials can easily be used. The major disadvantage is that optimum operation of such a device occurs at a specific pressure and temperature; variation of the conditions in the evaporator may well lead to a reduction in the economy which can be achieved.

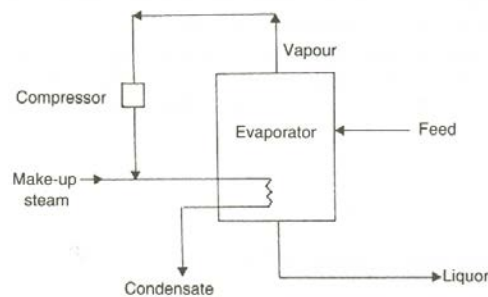


Fig. 27.3(a) Mechanical Vapor recompression

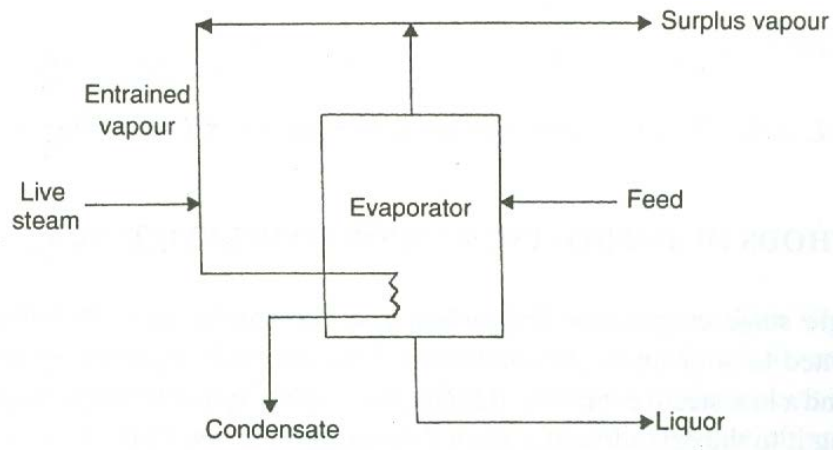


Fig. 27.3(b) Steam ejector vapor recompression

## LECTURE NO. 28

### SIZING OF MULTIPLE EFFECT EVAPORATORS

The rate equation can be written for each effect in turn

$$\begin{aligned}Q_1 &= U_1 A_1 \Delta T_1 \\Q_2 &= U_2 A_2 \Delta T_2 \\Q_3 &= U_3 A_3 \Delta T_3\end{aligned}\quad (28.1)$$

where the temperature differences are defined by

$$\begin{aligned}\Delta T_1 &= T_s - T_1 \\ \Delta T_2 &= T_1 - T_2 \\ \Delta T_3 &= T_2 - T_3\end{aligned}\quad (28.2)$$

and the subscripts 1, 2, and 3 refer to the first, second and third effects, respectively.

If now it is assumed that there is no boiling point rise, that the enthalpy required to raise the feed to the temperature  $T_1$  can be neglected and that the enthalpy carried by the concentrated liquor to subsequent effects is negligible, then the heat flux  $Q_1$  appears as the latent heat of the vapour in the calandria of effect 2. Therefore

$$Q_1 = Q_2 = Q_3 \quad (28.3)$$

and

$$U_1 A_1 \Delta T_1 = U_2 A_2 \Delta T_2 = U_3 A_3 \Delta T_3 \quad (28.4)$$

If each unit is geometrically similar each will have the same area and

$$U_1 \Delta T_1 = U_2 \Delta T_2 = U_3 \Delta T_3 \quad (28.5)$$

The total capacity of the evaporator  $Q$  is then given by

$$Q = Q_1 + Q_2 + Q_3 \quad (28.6)$$

and

$$Q = U_{av} A (\Delta T_1 + \Delta T_2 + \Delta T_3) \quad (28.7)$$

where  $A$  is the area of a *single* effect and  $U_{av}$  is an average overall heat transfer coefficient.

It is important to understand that a single effect evaporator will have approximately the same capacity  $Q$  as the multiple effect evaporator if the temperature difference is the same as the *total* temperature difference of the multiple effect unit, the area is the same as the area of *one* effect and the overall heat transfer coefficient is the same. The advantage of multiple effect evaporation is not an increased capacity but an increased steam economy. In an  $n$  effect evaporator 1 kg of steam evaporates approximately  $n$  kg of vapour. Thus the economy of the multiple effect system is greater but the capital cost is greatly increased. For  $n$  effects the capital cost will be approximately  $n$  times that of a single effect and the optimum number of effects is a balance between the capital cost on the one hand and the improved economy and therefore lower operating costs on the other.

In order to determine the area of a multiple effect evaporator an iterative calculation is required. If the likely values of the overall heat transfer coefficient for each effect are known then, together with the temperature in the final effect (which is a function of the degree of vacuum applied), a first approximation of the temperature differences  $\Delta T_1, \Delta T_2$  and  $\Delta T_3$  can be obtained from Equation (28.4). This will give the temperature in each effect from which the enthalpies of vaporization can be found and hence the material and energy balances can be solved to give the steam and vapour flow rates. A first approximation of the area of each effect can now be made from the rate equations [Equation (27.9)]. Because of the assumptions made in this procedure, it is very likely that this first iteration will give unequal areas. A new approximation of each temperature difference is now obtained from an equation of the form

$$new \Delta T_1 = \frac{\Delta T_1 A_1}{A_{mean}} \quad (28.8)$$

where  $A_{mean}$  is the average of each effect area. This calculation is repeated until the areas of each effect are sufficiently close together.

### Example 5

A 4% aqueous food solution is fed at a rate of  $2.0 \text{ kg s}^{-1}$  and a temperature of  $70^\circ\text{C}$  to a forward feed double-effect evaporator with equal

surface areas. The solution is concentrated to 20% by mass. The second effect is maintained at a pressure of 20 kPa with a boiling point elevation of 8 K. Steam at 240 kPa is available. The heat transfer coefficients in the first and second effects are  $2.20$  and  $1.50 \text{ kW m}^{-2} \text{ K}^{-1}$ , respectively, and the heat capacity of each liquid stream may be assumed to be  $4.18 \text{ kJ.kg}^{-1} \text{ K}^{-1}$ . Calculate the heat transfer surface area of each effect and the economy.

A component material balance gives

$$0.04 \times 2.0 = 0.20 L_2$$

and therefore the flow rate of concentrate from the second effect  $L_2$  equals  $0.40 \text{ kg s}^{-1}$ . From an overall balance the total vapour generated  $V$ , equal to  $V_1 + V_2$ , is then  $(2.0 - 0.40) = 1.60 \text{ kg s}^{-1}$ . The steam temperature at 240 kPa is  $T_s = 126.1^\circ\text{C}$ . The temperature in the second effect is equal to the boiling point of water at 20 kPa plus the boiling point elevation, thus

$$T_2 = 60.1 + 8.0 = 68.1^\circ\text{C}$$

and the overall temperature difference, equal to  $\Delta T_1 + \Delta T_2$ , is  $(126.1 - 68.1) = 58 \text{ K}$ . Now from Equation (28.5)

$$2.20 \Delta T_1 = 1.50 \Delta T_2$$

and consequently  $\Delta T_1 = 23.5 \text{ K}$  and  $\Delta T_2 = 34.5 \text{ K}$ . From Equation 11 the temperature in the first effect  $T_1$  is  $(126.1 - 23.5) = 102.6^\circ\text{C}$ . Ignoring the enthalpy of the stream  $L_1$ , an enthalpy balance over the first effect can now be written as

$$S(h_s - h_c) + Fc_p(T_F - T_1) = V_1 h_{v1}$$

where  $h_{v1}$ , represents the enthalpy of vapour at  $T_1$  and  $T_F$  is the feed temperature. Thus

$$2185 S + (2.0 \times 4.18 (70 - 102.6)) = 2680.4 V_1$$

and

$$2185 S = 2680.4 V_1 + 272.5 \quad (\text{i})$$

The enthalpy balance over the second effect, ignoring the stream  $L_2$ , is

$$V_1 h_{fg1} + (F - V_1) c_p (T_2 - T_1) = V_2 h_{v2}$$

where  $h_{fg1}$ , represents the latent heat of vapor is at ion at  $T_1$ . Thus

$$2250.2V_1 + (2.0 - V_1) 4.18(102.6 - 68.1) = 2623 V_2$$

which simplifies to

$$2106.0 V_1 + 288.4 = 2623V_2 \quad (\text{ii})$$

From the material balance

$$V_1 + V_2 = 1.60$$

(iii)

Now solving (i) -- (iii) simultaneously yields

$$V_1 = 0.826 \text{ kg s}^{-1}$$

$$V_2 = 0.774 \text{ kgs}^{-1}, \quad S = 1.138 \text{ kgs}^{-1}$$

Hence the first estimate of the area of each effect can be obtained from the rate equation [Equation (28.1)] and

$$A_1 = \frac{1.138 \times 2185.0}{2.20 \times 23.50} m^2, \text{ or } A_1 = 48.1 m^2$$

Similarly

$$A_2 = \frac{0.826 \times 2250.2}{1.50 \times 34.50} m^2, \text{ or } A_2 = 35.9 m^2$$

The values of  $A_1$  and  $A_2$  are not equal and a second iteration is necessary. The temperature difference  $\Delta T_1$  is now amended using Equation (28.8).

$$\text{new } \Delta T_1 = \frac{\Delta T_1 A_1}{(A_1 + A_2) / 2}$$

Therefore

$$\Delta T_1 = \frac{23.5 \times 48.1}{(48.1 + 35.9) / 2} K, \quad \Delta T_1 = 26.9 K$$

By difference the amended temperature driving force for the second effect is  $\Delta T_2 = 31.1 K$ .

The procedure is now to recalculate  $T_1$  which becomes  $(126.1 - 26.9) = 99.2^\circ C$ , determine new values of  $h_{v1}$ , and  $h_{fg1}$ , from steam tables, repeat the calculation of  $V_1, V_2$ , and  $S$  and so on. This produces

$$V_1 = 0.825 \text{ kg s}^{-1}, \quad V_2 = 0.775 \text{ kg s}^{-1}, \quad S = 1.122 \text{ kg s}^{-1}$$

The area of the first effect is now

$$A_1 = \frac{1.122 \times 2185.0}{2.20 \times 26.9} m^2, \text{ or } A_1 = 41.4 m^2$$

and that of the second effect is

$$A_2 = \frac{0.825 \times 2280.8}{1.50 \times 31.1} m^2, \text{ or } A_2 = 40.3 m^2$$

The estimates of the two areas are now sufficiently close together giving a mean heat transfer surface area of 40.9 m<sup>2</sup>. Two iterations are therefore sufficient. The economy is now equal to the total vapour produced (1.60 kg.s<sup>-1</sup>) divided by the steam flow rate of 1.122 kgs<sup>-1</sup>. Thus the economy at 1.426 is greater than unity.

## LECTURE NO. 29

THIN LAYER DRYING, MOISTURE CONTENT, EQUILIBRIUM MOISTURE CONTENT, HYSTERESIS, DRYING CURVES, CONSTANT - RATE PERIOD, FALLING - RATE PERIOD

### DRYING

Generally the term drying refers to the removal of relatively small amount of moisture from a solid or nearly solid material by evaporation. Therefore, drying involves both heat and mass transfer operations simultaneously. Because of the basic differences in drying characteristics of grains in thin layer and deep bed, the whole grain drying process is divided into thin layer drying and deep bed drying.

### THIN LAYER DRYING

Thin layer drying refers to the grain drying process in which all grains are fully exposed to the drying air under constant drying conditions, i.e., at constant air temperature, and humidity. Generally up to 20 cm thickness of grain bed (with a recommended air-grain ratio) is taken as thin layer. All **commercial flow dryers** are designed on thin layer drying principles. Terms used in describing the drying process are:

#### **Moisture content**

Usually the moisture content of a substance is expressed in percentage by weight on wet basis. But the moisture content on dry, basis is simpler to use in calculation as the quantity of moisture present at any time is directly proportional, to the moisture content on dry basis.

The moisture content,  $m$ , per, cent, wet basis is:

$$m = \frac{W_m}{W_m + W_d} \times 100$$

where

$W_m$  = weight of moisture and

$W_d$  = weight of bone dry material.

The moisture content,  $M$ , dry basis, per cent is :

$$M = \frac{W_m}{W_d} \times 100 = \frac{m}{100 - m} \times 100$$



The moisture content,  $X$ , dry basis is sometimes expressed in decimal also:

$$X = \frac{M}{100}$$

### Moisture measurement

Moisture content can be determined by direct and indirect methods. Direct method includes air-oven drying method ( $130^{\circ} \pm 2^{\circ} \text{C}$ ) and distillation method. Direct methods are simple and accurate but time consuming whereas indirect methods are convenient and quick but less accurate.

### Equilibrium moisture content

When a solid is exposed to a continual supply of air at constant temperature and humidity, having a fixed partial pressure of the vapour;  $p$  the solid will either lose moisture by evaporation or gain moisture from the air until the vapour pressure of the moisture of the solid equals  $p$ . The solid and the gas are then in equilibrium, and the moisture content of the solid in equilibrium with the surrounding conditions is known as equilibrium moisture content E.M.C. (Fig. 29.1). The E.M.C. is useful to determine whether a product will gain or lose moisture under a given set of temperature and relative humidity conditions.

A plot of the equilibrium relative humidity and moisture content of a particular material at a particular temperature (usually  $25^{\circ} \text{C}$ ) is known as equilibrium moisture curve or isotherm. Grain isotherms are generally S-shaped and attributed to multi-molecular adsorption.

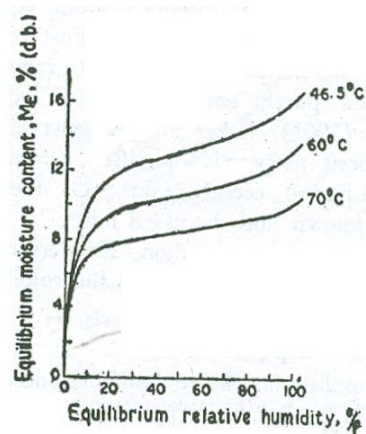


Fig.29.1 Desorption isotherms for paddy

### DETERMINATION OF EQUILIBRIUM MOISTURE CONTENT,

Generally EMC is determined by two methods: (a) the static method, and (b) the dynamic method. In the static method, the grain is allowed to come to

equilibrium with the surrounding still air without any agitation, whereas in the dynamic method, the air is generally mechanically moved.

### E.M.C. Models

A number of E.M.C. equations namely BET equation, Harkin and Jura equation, Smith equation, Henderson equation, Chung and Fost equation, etc., have been developed for different ranges of relative humidities.

The Henderson's equation to express the equilibrium moisture content is :

$$1 - RH = \exp[-cTM_e^n]$$

Where,

$RH$  = equilibrium relative humidity, decimal

$M_e$  = E.M.C., dry basis, per cent

$T$  = temperature, K and

$c$  and  $n$  = product constants, varying with materials.

### Hysteresis

Many solid materials including cereal grains exhibit different equilibrium moisture characteristics depending upon whether the equilibrium is reached by adsorption / sorption or desorption of the moisture. This phenomenon is known as hysteresis which is shown in the following figure 29.2.

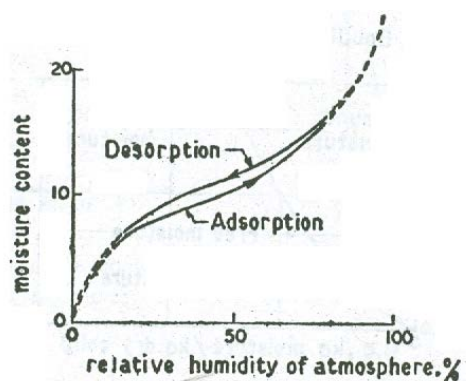


Fig. 29.2 Relation between equilibrium moisture content of paddy and relative humidity showing hysteresis

### Bound moisture

This refers to the moisture-contained by a substance which exerts equilibrium vapour pressure, less than that of the pure liquid at the same temperature (Fig.29.3). The bound moisture may be contained, inside the cell walls of the plant structure, moisture in loose chemical combination with the cellulosic material, moisture bound in small capillaries and crevasses through out the solid.

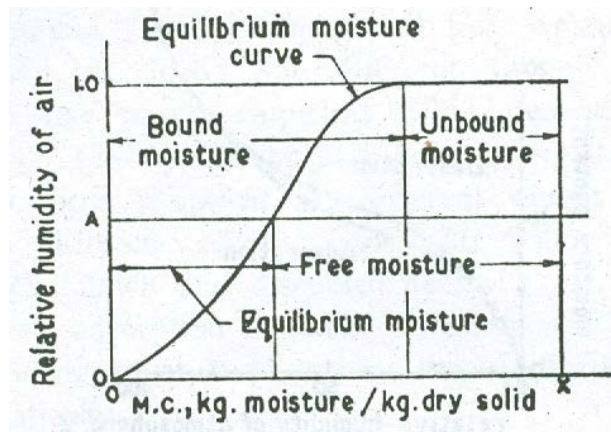


Fig. 29.3 Types of Moisture

### **Unbound moisture**

This refers to the moisture contained by a substance which exerts equilibrium vapour pressure equal to that of the pure liquid at the same temperature (Fig.29.3).

### **Free moisture**

Free moisture is the moisture contained by a substance in excess of the equilibrium moisture,  $X - X_E$ . (Fig.29.3 ). Only free moisture can be evaporated and the free water content of a solid depends upon the vapour concentration in the air.

### **Drying Curves**

A typical drying curve is shown in Fig.29.4. The figure clearly shows that there are two - major periods of drying, namely, the constant-rate period and the falling rate period.

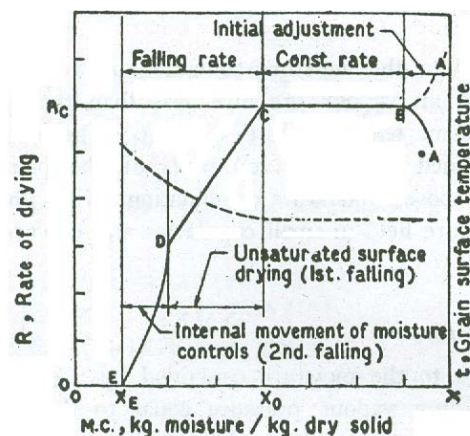


Fig.29.4 Typical drying rate curve, constant drying condition.

The plots of moisture content versus drying time or drying rate versus drying time or drying rate versus moisture content are known as drying curves (Figs.29.5 and 29.6)

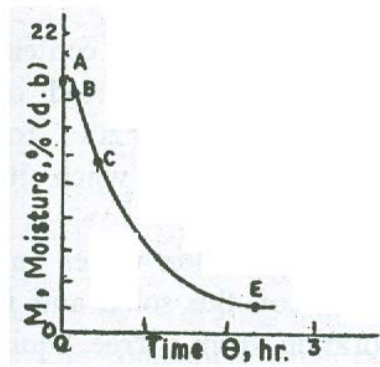


Fig. 29.5 Moisture content versus drying time

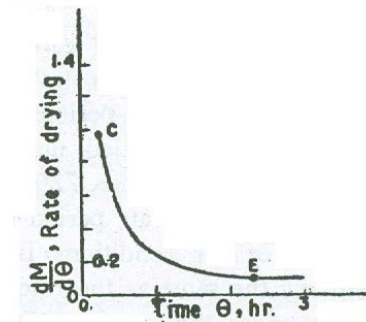


Fig.29.6 Drying rate versus drying time

### Constant-rate period

Some crops including cereal grains at high moisture content are dried under constant-rate period at the initial period of drying. Falling-rate period follows subsequently. As for example, wheat is dried under constant-rate period when its moisture content exceeds 72%.

In the constant-rate period the rate of evaporation under any given set of air conditions is independent of the solid and is essentially the same as the rate of evaporation from a free liquid surface under the same condition. The rate of drying during this period is dependent upon: (a) difference between the temperature of air and temperature of the wetted surface at constant air velocity and relative humidity, (b) difference in humidity between air stream and wet surface at constant air velocity and temperature, and (c) air velocity at constant air temperature and humidity.

In the constant-rate period drying takes place by surface evaporation and moisture moves by vapour pressure difference. The moisture content at which the drying rate ceases to be constant is known as the critical moisture content of the solid. The average critical moisture content,  $X_c$  for a given type of material depends upon the surface moisture concentration, bed thickness of the material and rate of drying. The critical moisture content of a product also depends upon the characteristics of the solid such as shape, size and the drying conditions.

If the drying takes place entirely within the constant-rate period so that  $X_1, X_2 > X_c$ .

$$\text{Then by definition, } R = -\frac{W_d}{A} \frac{dX}{d\theta}$$

Separating the variables and integrating the equation within proper limits, we get:

$$\text{time of drying, } \theta_c = \frac{W_d}{A} \left( \frac{X_1 - X_2}{R_c} \right)$$

where

$W_d$  = Weight of dry solid, kg

$A$  = Wet surface,  $m^2$

$X_1$  = Initial moisture content, kg moisture/kg dry solid

$X_2$  = Final moisture content, kg/kg

$X_c$  = Critical moisture content, kg/kg

$R_c$  = Rate of drying in the constant rate period, kg moisture evaporated / hr. $m^2$

$\theta_c$  = drying time, hr.

### **Falling-rate period**

Cereal grains are usually dried entirely under falling-rate period.

The falling rate period enters after the constant drying rate period and corresponds to the drying cycle where all surface is no longer wetted and the wetted surface continually decreases, until at the end of this period the surface is dry. The cause of falling off in the rate of drying is due to the inability of the moisture to be conveyed from the centre of the body to the surface at a rate comparable with the moisture evaporation from its surface to the surroundings.

The falling-rate period is characterized by increasing temperatures both at the surface and within the solid.

### **DEEP BED DRYING**

In deep bed drying all the grains in the dryer are not fully exposed to the same condition of drying air. The condition of drying air at any point in the grain mass changes with time and at any times it also changes with the depth of the grain bed. Over and above the rate of air flow per unit mass of grain is small

compared to the thin layer drying of grain. All on-farm static bed batch dryers are designed on deep bed drying principle. The condition of drying in deep bed is shown in the following Figure 29.7.

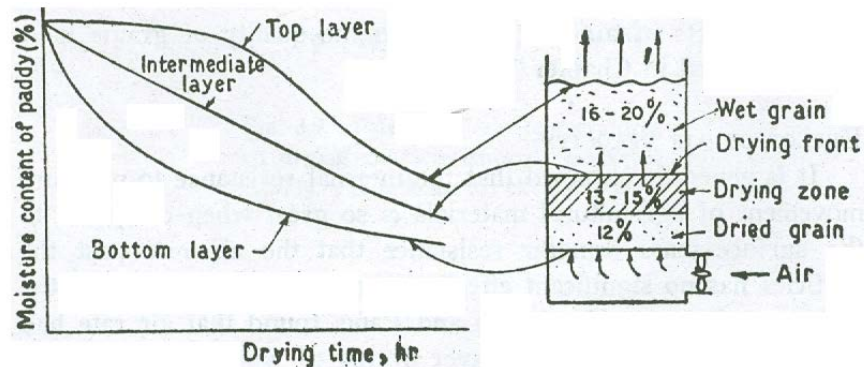


Fig.29.7 Deep bed drying characteristics at different depths.

The drying of grain in a deep bin can be taken as the sum of several thin layers. The humidity and temperature of air entering and leaving each layer vary with time depending upon the stage of drying, moisture removed from the dry layer until the equilibrium moisture content is reached. Little moisture is removed, rather a small amount may be added to the wet zone until the drying zone reaches it. The volume of drying zone varies with the temperature and humidity of entering air, the moisture content of grain and velocity of air movement. Drying will cease as soon as the product comes in equilibrium with the air.

#### **Time of advance of drying front**

The time period taken by the drying front to reach the top of the bin is called the maximum drying rate period.

## LECTURE NO. 30

TRAY AND CABINET DRYER, TUNNEL DRYER, PUFF-DRYING, FLUIDIZED - BED DRYING, SPRAY DRYING, FREEZE - DRYING

### Different Types of Dryers

#### Tray or Cabinet Dryers

These types of dryers use trays or similar product holders to expose the product to heated air in an enclosed space. The trays holding the product inside a cabinet or similar enclosure (Fig.30.1) are exposed to heated air so that dehydration will proceed. Air movement over the product surface is at relatively high velocities to ensure that heat and mass transfer will proceed in an efficient manner.

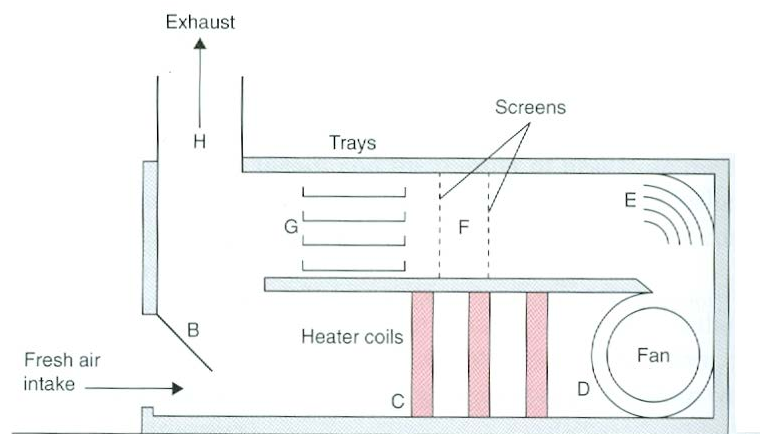


Fig.30.1 Cabinet Type Tray Drier

In most cases, cabinet dryers are operated as batch systems and have the disadvantage of non-uniform drying of a product at different locations within the system. Normally, the product trays must be rotated to improve uniformity of drying.

#### Tunnel Dryers

Figures 30.2(a) and 30.2(b) show examples of tunnel dryers. As illustrated, the heated drying air is introduced at one end of the tunnel and moves at an established velocity through trays of products being carried on trucks. The product trucks are moved through the tunnel at a rate required to maintain the residence time needed for dehydration. The product can be moved in the same direction as the air flow to provide concurrent dehydration (Fig. 30.2(a)), or the tunnel can be operated in counter current manner (Fig. 30.2(b)),



with the product moving in the direction opposite to air flow. The arrangement used will depend on the product and the sensitivity of quality characteristics to temperature.

With concurrent systems, a high-moisture product is exposed to high temperature air, and evaporation assists in maintaining lower product temperature. At locations near the tunnel exit, the lower-moisture product is exposed to lower-temperature air. In counter current systems, a lower-moisture product is exposed to high-temperature air, and a smaller temperature gradient exists near the product entrance to the tunnel.

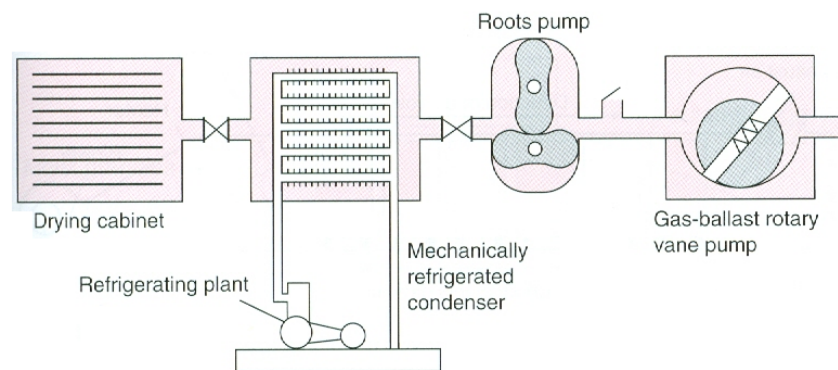


Fig. 30.2(a) A concurrent flow tunnel dryer

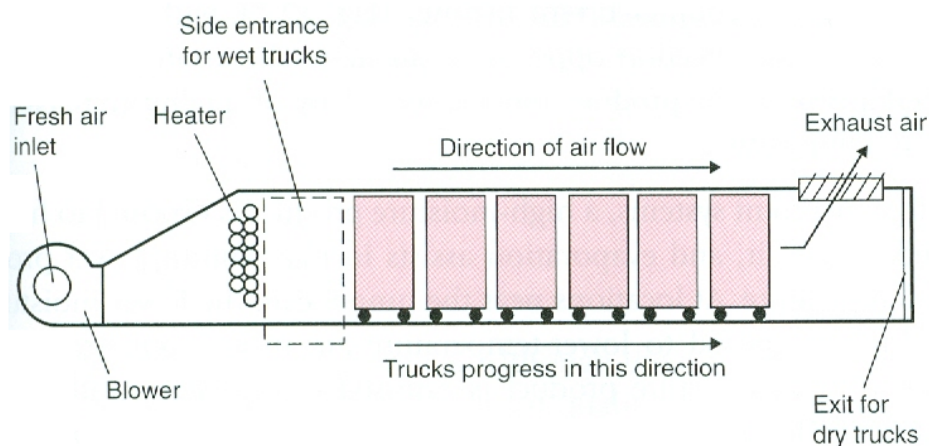


Fig. 30.2(b) A counter current flow tunnel dryer

## Puff-Drying

In this drying process foods are dried by explosion puff-drying. This process is accomplished by exposing a relatively small piece of product to high pressure and high temperature for a short time, after which the product is moved to atmospheric pressure. This results in flash evaporation of water and allows vapors from the interior parts of the product to escape. Products produced by



puff-drying have very high porosity with rapid rehydration characteristics. Puff-drying is particularly effective for products with significant falling-rate drying periods. The rapid moisture evaporation and resulting product porosity contribute to rapid moisture removal during the final stages of drying. The puff-drying process is accomplished most efficiently by using 2 cm cube shapes. These pieces will dry rapidly and uniformly and will rehydrate within 15 minutes.

### Fluidized-Bed Drying

In this system, the product pieces are suspended in the heated air throughout the time required for drying. As illustrated in Figure 30.3, the movement of product through the system is enhanced by the change in mass of individual particles as moisture is evaporated. The movement of the product created by fluidized particles results in equal drying from all product surfaces. The primary limitation to the fluidized-bed process is the size of particles that will allow efficient drying. As would be expected, smaller particles can be maintained in suspension with lower air velocities and will dry more rapidly. Not all products can be adapted dried with this process.

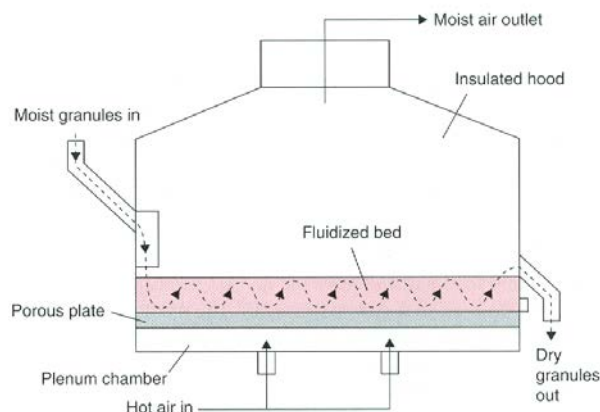


Fig.30.3 Fluidized bed drier

### Spray Drying

The drying of liquid food products is often accomplished in a spray dryer. Moisture removal from a liquid food occurs after the liquid is atomized or sprayed into heated air within a drying chamber. Although various configurations of the chamber are used, the arrangement shown in Figure 30.4 illustrates the introduction of liquid droplets into a heated air stream.

While liquid food droplets are moving with the heated air, the water evaporates and is carried away by the air. Much of the drying occurs during a constant-rate period and is limited by mass transfer at the droplet surface. After reaching the critical moisture content, the dry food particle structure influences the falling-rate drying period. During this portion of the process, moisture diffusion within the particle becomes the rate-limiting parameter.

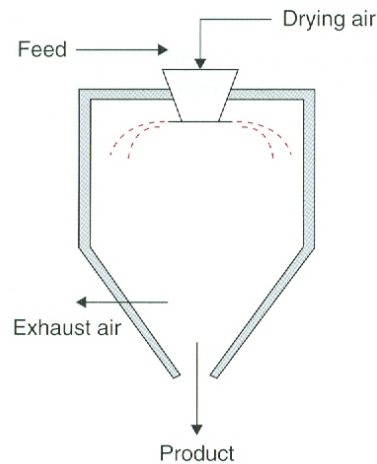


Fig.30.4 Spray drying System

After the dry food particles leave the drying chamber, the product is separated from air in a cyclone separator. The dried product is then placed in a sealed container at moisture contents that are usually below 5%. Product quality is considered excellent due to the protection of product solids by evaporative cooling in the spray dryer. The small particle size of dried solids promotes easy reconstitution when mixed with water.

### Freeze-Drying

Freeze-drying is accomplished by reducing the product temperature so that most of the product moisture is in a solid state, and by decreasing the pressure around the product, sublimation of ice can be achieved. When product quality is an important factor for consumer acceptance, freeze-drying provides an alternative approach for moisture removal.

The heat- and mass-transfer processes during freeze-drying are unique. Depending on the configuration of the drying system (Fig.30.5), heat transfer can occur through a frozen product layer or through a dry product layer. Obviously, heat transfer through the frozen layer will be rapid and not rate-

limiting. Heat transfer through the dry product layer will be at a slow rate due to the low thermal conductivity of the highly porous structure in a vacuum. In both situations, the mass transfer will occur in the dry product layer. The diffusion of water vapor would be expected to be the rate-limiting process because of the low rates of molecular diffusion in a vacuum.

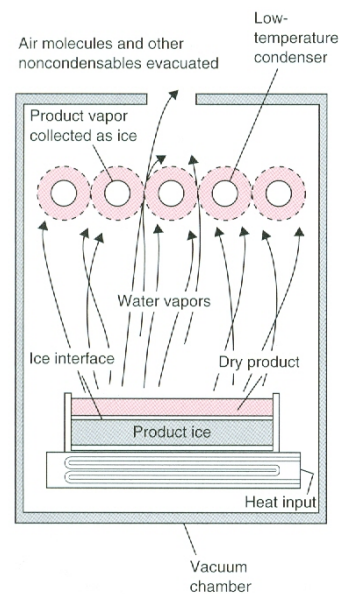


Fig.30.5 Freeze drying System

## LECTURE NO. 31

### INTRODUCTION TO HEAT PROCESSING - BLANCHING, PASTEURIZATION, STERILIZATION

#### THERMAL PROCESSING OF FOODS

##### BLANCHING

One of the main objective of the blanching is to destroy enzymic activity in vegetables and some fruits, prior to further processing. Blanching is combined with peeling and/or cleaning of food, to achieve savings in energy consumption, space and equipment costs. To achieve adequate enzyme inactivation, food is heated rapidly to a pre-set temperature, held for a pre-set time and then cooled rapidly to near ambient temperatures. The factors which influence blanching time are:

- type of fruit or vegetable
- size of the pieces of food
- blanching temperature
- method of heating.

The maximum processing temperature in freezing and dehydration is insufficient to inactivate enzymes. In canning, the time taken to reach sterilizing temperatures, particularly in large cans, may be sufficient to allow enzyme activity to take place. It is therefore necessary to blanch foods prior to these preservation operations. Under blanching may cause more damage to food.

The heat resistance of enzymes is characterized by  $D$  and  $z$  values (Chapter 1). Enzymes which cause a loss of eating and nutritional qualities in vegetables and fruits include lipxygenase, polyphenoloxidase, polygalacturonase and chlorophyllase. Two heat-resistant enzymes which are found in most vegetables are catalase and peroxidase. Although they do not cause deterioration during storage, they are used as marker enzymes to determine the success of blanching. Peroxidase is the more heat resistant of the two, so the absence of residual peroxidase activity would indicate that other less heat-resistant enzymes are also destroyed. The factors that control the rate of heating at the centre of the product are:

- the temperature of the heating medium
- the convective heat transfer coefficient
- the size and shape of the pieces of food

- the thermal conductivity of the food.

## Equipment

The two most widespread commercial methods of blanching involve passing food through an atmosphere of saturated steam or a bath of hot water. Both types of equipment are relatively simple and inexpensive. Steam blanching results in higher nutrient retention provided that cooling is by cold-air or cold-water sprays.

### Steam blanchers

At its simplest a steam blancher consists of a mesh conveyor belt that carries food through a steam atmosphere in a tunnel. The residence time of the food is controlled by the speed of the conveyor and the length of the tunnel. Typically a tunnel is 15 m long and 1–1.5 m wide. The efficiency of energy consumption is 19% when water sprays are used at the inlet and outlet to condense escaping steam. Alternatively, food may enter and leave the blancher through rotary valves or hydrostatic seals to reduce steam losses and increase energy efficiency to 27%, or steam may be re-used by passing through Venturi valves. Energy efficiency is improved to 31% using combined hydrostatic and Venturi devices.

Nutrient losses during steam blanching are reduced by exposing the food to warm air (65°C) in a short preliminary drying operation (termed '*pre-conditioning*'). Surface moisture evaporates and the surfaces then absorb condensing steam during **Individual Quick Blanching (IQB)**. Weight losses are reduced to 5% of those found using conventional steam blanching. Pre-conditioning and individual quick blanching are reported to reduce nutrient losses by 81% for green beans, by 75% for Brussels sprouts, by 61% for peas and by 53% for lima beans and there is no reduction in the yield of blanched food.

The equipment for IQB steam blanching (Fig.31.1(a)) consists of a bucket elevator which carries the food to a heating section. The elevator is located in a close fitting tunnel to reduce steam losses. A single layer of food is heated on a conveyor belt and then held on a holding elevator before cooling. The cooling section employs a fog spray to saturate the cold air with moisture. This reduces evaporative losses from the food and reduces the amount of effluent produced. Typically the equipment processes up to 4500 kg/h of food.

## Hot-water blanchers

There are a number of different designs of blancher, each of which holds the food in hot water at 70–100°C for a specified time and then removes it to a dewatering-cooling section.

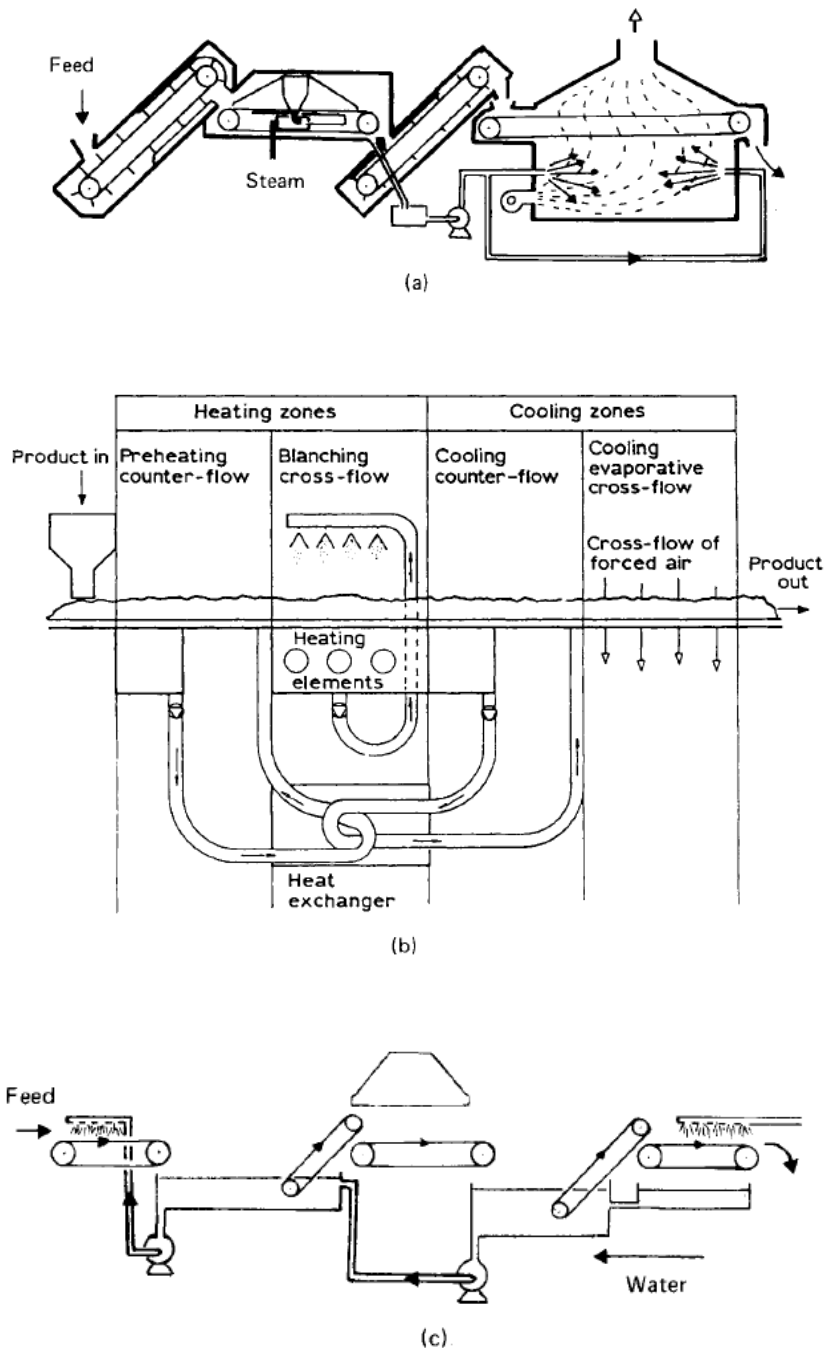


Fig. 31.1 Blanchers: (a) IQB steam blancher (b) blancher-cooler and (c) counter-current blancher

Developments in hot-water blanchers, based on the IQB principle, reduce energy consumption and minimize the production of effluent. For example, **the blancher-cooler** has three sections: a pre-heating stage, a blanching stage and a cooling stage (Fig.31.1 (b)). The food remains on a single conveyor belt

throughout each stage and therefore does not suffer the physical damage associated with the turbulence of conventional hot water blanchers. The food is pre-heated with water that is re-circulated through a heat exchanger. After blanching, a second recirculation system cools the food. The two systems pass water through the same heat exchanger, and this heats the pre-heat water and simultaneously cools the cooling water. Up to 70% of the heat is recovered. A recirculated water-steam mixture is used to blanch the food, and final cooling is by cold air. Effluent production is negligible and water consumption is reduced to approximately 1m<sup>3</sup> per 10 t of product. The mass of product blanched is 16.7 – 20 kg per kilogram of steam, compared with 0.25–0.5 kg per kilogram in conventional hot-water blanchers.

In another design, used for blanching broccoli, lima beans, spinach and peas, is the water and food move counter-currently (Fig.31.1(c)).

### **Pasteurization**

Pasteurization is a relatively mild heat treatment, in which food is heated to below 100°C. In low acid foods (pH > 4.5, for example milk) it is used to minimize possible health hazards from pathogenic micro-organisms and to extend the shelf life of foods for several days. In acidic foods (pH < 4.5, for example bottled fruit) it is used to extend the shelf life for several months by destruction of spoilage micro-organisms (yeasts or moulds) and/or enzyme inactivation.

The extent of the heat treatment required to stabilize a food is determined by the *D* value of the most heat-resistant enzyme or micro-organism. As flavors, colors and vitamins are also characterized by *D* values, pasteurization conditions can be optimized for retention of nutritional and sensory quality by the use of high-temperature short-time (HTST) conditions. For example in milk processing the lower temperature longer time (LTLT) process operating at 63°C for 30 min (the *holder* process) causes greater changes to flavour and a slightly greater loss of vitamins than HTST processing at 71.8°C for 15 s and it is less often used. Higher temperatures and shorter times (for example 88°C for 1 s, 94°C for 0.1 s or 100 °C for 0.01 s for milk) are described as higher-heat shorter-time processing or ‘flash pasteurization’.

### **Equipment Used**

#### **Pasteurization of packaged foods**

Some liquid foods (for example beers and fruit juices) are pasteurised after filling into containers. Hot water is normally used if the food is packaged in glass, to reduce the risk of thermal shock to the container (fracture caused by rapid changes in temperature). Maximum temperature differences between the container and water are 20 °C for heating and 10 °C for cooling. Metal or plastic containers are processed using steam–air mixtures or hot water as there is little risk of thermal shock. In all cases the food is cooled to approximately 40 °C to evaporate surface water and therefore to minimize external corrosion to the container or cap, and to accelerate setting of label adhesives.

Hot-water pasteurizers may be batch or continuous in operation. The simplest batch equipment consists of a **water bath** in which crates of packaged food are heated to a pre-set temperature and held for the required length of time. Cold water is then pumped in to cool the product. A continuous version consists of a long narrow trough fitted with a conveyor belt to carry containers through heating and cooling stages.

A second design consists of a tunnel divided into a number of heating zones. Very fine (atomized) water sprays heat the containers as they pass through each zone on a conveyor, to give incremental rises in temperature until pasteurization is achieved. Water sprays then cool the containers as they continue through the tunnel.

### **Pasteurization of unpackaged liquids**

Swept surface heat exchangers or open boiling pans are used for small-scale batch pasteurization of some liquid foods. However, the large scale pasteurization of low viscosity liquids (for example milk, milk products, fruit juices, liquid egg, beers and wines) usually employs **plate heat exchangers**. Some products (for example fruit juices, wines) also require de-aeration to prevent oxidative changes during storage. They are sprayed into a vacuum chamber and dissolved air is removed by a vacuum pump, prior to pasteurization.

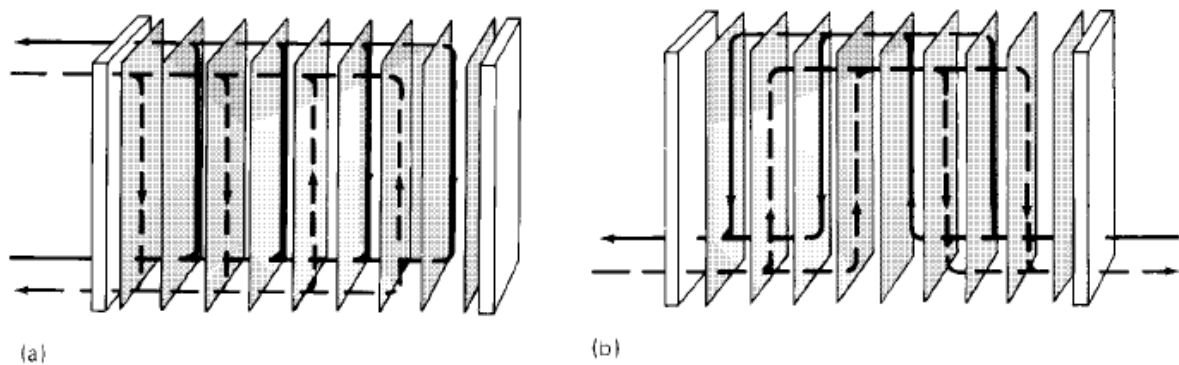
The *plate heat exchanger* (Fig.31.2) consists of a series of thin vertical stainless steel plates, held tightly together in a metal frame. The plates form parallel channels, and liquid food and heating medium (hot water or steam) are pumped through alternate channels, usually in a counter-current flow pattern (Fig.31.3). Each plate is fitted with a synthetic rubber gasket to produce a watertight seal and to prevent mixing of the product and the heating and cooling



media. The plates are corrugated to induce turbulence in the liquids and this, together with the high velocity induced by pumping, reduces the thickness of boundary films to give high heat transfer coefficients ( $3000 - 11500 \text{ W m}^{-2} \text{ K}^{-1}$ ). The capacity of the equipment varies according to the size and number of plates, up to  $80\,000 \text{ l h}^{-1}$ .



Fig.31.2 Plate heat exchanger.



31.3 Counter-current flow through plate heat exchanger:

- (a) one pass with four channels per medium;
- (b) two passes with two channels per pass and per medium.

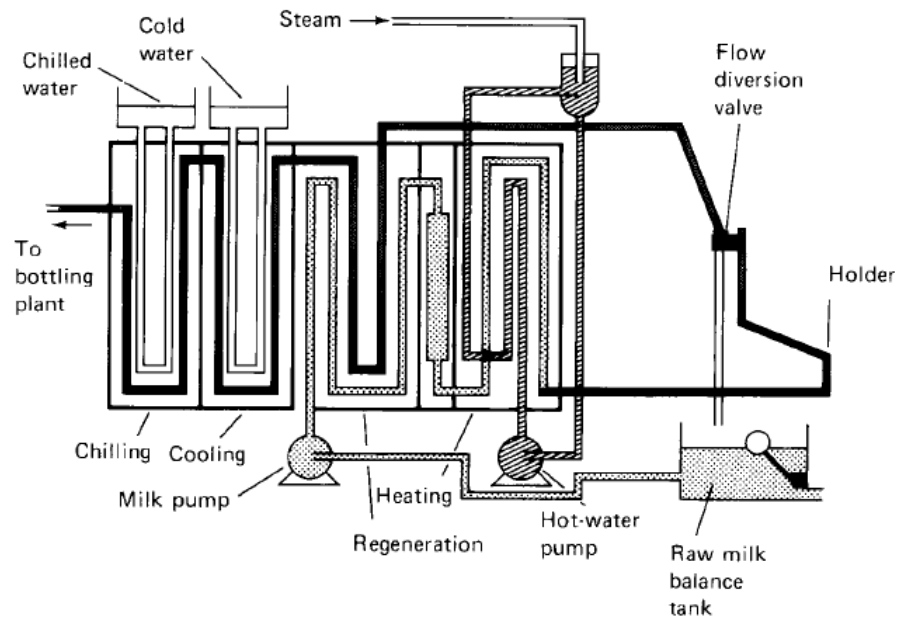


Fig.31.4 Pasteurizing using a plate heat exchanger.

In operation (Fig.31.3), food is pumped from a balance tank to a 'regeneration' section, where it is pre-heated by food that has already been pasteurised. It is then heated to pasteurizing temperature in a heating section and held for the time required to achieve pasteurization in a holding tube. If the pasteurizing temperature is not reached, a flow diversion valve automatically returns the food to the balance tank to be repasteurized. The pasteurized product is then cooled in the regeneration section (and simultaneously preheats incoming food) and then further cooled by cold water and, if necessary, chilled water in a cooling section.

### **Heat sterilization**

Heat sterilization is the unit operation in which foods are heated at a sufficiently high temperature and for a sufficiently long time to destroy microbial and enzyme activity. As a result, sterilized foods have a shelf life in excess of six months at ambient temperatures.

#### **In-container sterilization**

The length of time required to sterilize a food is influenced by:

- the heat resistance of micro-organisms or enzymes likely to be present in the food
- the heating conditions
- the pH of the food
- the size of the container

- the physical state of the food.

In order to determine the process time for a given food, it is necessary to have information about both the heat resistance of micro-organisms, particularly heat resistant spores, or enzymes that are likely to be present and the rate of heat penetration into the food.

### **Retorting (heat processing)**

The shelf life of sterilized foods depends in part on the ability of the container to isolate the food completely from the environment. The four major types of heat-sterilisable container are:

1. metal cans
2. glass jars or bottles
3. flexible pouches
4. rigid trays.

Before filled containers are processed, it is necessary to remove air by an operation termed '**exhausting**'. This prevents air expanding with the heat and therefore reduces strain on the container. The removal of oxygen also prevents internal corrosion and oxidative changes in some foods. Steam replaces the air and on cooling forms a partial vacuum in the head space.

Containers are exhausted by:

hot filling the food into the container

cold filling the food and then heating the container and contents to 80–95°C with the lid partially sealed (clinched)

mechanical removal of the air using a vacuum pump

steam flow closing, where a blast of steam (at  $34 - 41.5 \times 10^3$  Pa) carries air away from the surface of the food immediately before the container is sealed. This method is best suited to liquid foods where there is little air trapped in the product and the surface is flat and does not interrupt the flow of steam.

### **Equipment**

Sterilising retorts may be batch or continuous in operation. Batch retorts may be vertical or horizontal; the latter are easier to load and unload and have facilities for agitating containers, but require more floor space. For example, the 'Orbitort' consists of a pressure vessel that contains two concentric cages. Cans are loaded horizontally into the annular space between the cages and when full, the retort is sealed. The cages hold the cans against guide rails as they are slowly rotated to cause the headspace bubble to stir the contents.

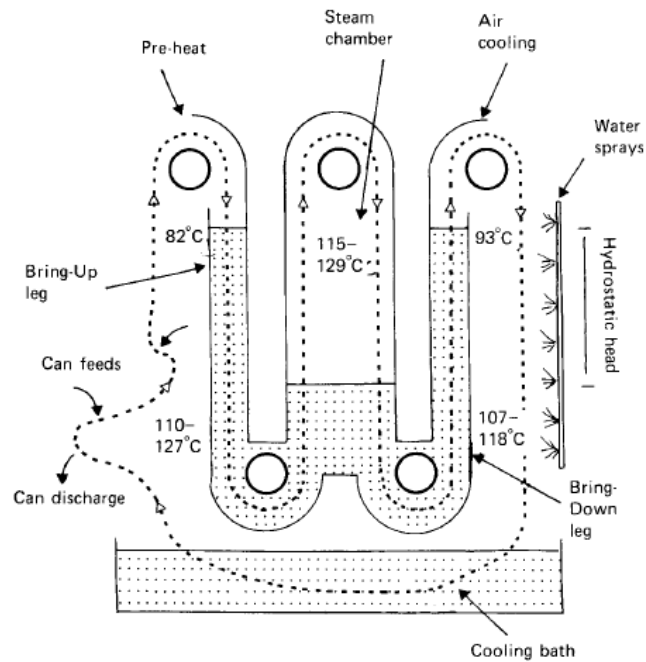


Fig. 31.5 Continuous hydrostatic steriliser.

Continuous retorts (for example, Fig 31.5) permit close control over the processing conditions and hence produce more uniform products. They produce gradual changes in pressure inside cans, and therefore less strain on the can seams compared with batch equipment. The main disadvantages include a high in-process stock which would be lost if a breakdown occurred, and in some, problems with metal corrosion and contamination by thermophilic bacteria if adequate preventative measures are not taken.

## LECTURE NO. 32

### KINETICS OF MICROBIAL DEATH, DECIMAL REDUCTION TIME AND THERMAL RESISTANCE CONSTANT, PROCESS LETHALITY

#### KINETICS OF MICROBIAL DEATH

The destruction of micro-organisms in foods using heat is a well-known phenomenon in the preservation techniques of foods. However the temperature response of vegetative cells and spores is **far from uniform**. Spores tend to be more heat resistant than vegetative cells which in turn range widely in their heat resistance. Even individual bacteria within a population of a given species show a normal distribution of heat resistance. Thus it is possible to allow heat resistant (or thermoduric) organisms to survive by using a heating regime which is sufficient to destroy bacteria of low to intermediate heat resistance but which fails to kill thermoduric bacteria. These may then thrive within a processing unit, for example, a blancher, and increase the microbial load on a subsequent sterilization operation.

The heat resistance of micro-organisms is also affected by a number of other factors such as:

1. the age of cells; younger cells are less heat resistant,
2. the medium in which growth has occurred; a more nutritious medium increases heat resistance,
3. moisture content; dry foods tend to require more severe heat treatment during sterilization,
4. the presence of sodium chloride, proteins and fats all increase heat resistance,
5. pH.

#### Decimal Reduction Time and Thermal Resistance Constant

The decline in the number of micro-organisms when subjected to heat is asymptotic with time and therefore it is not possible to eliminate all microorganisms. There is a logarithmic relationship between the number of survivors of a given microorganism ' $n$ ' and time ' $t$ ' at any given temperature (Figure 32.1 ). This is known as a **survivor curve**. The gradient of the survivor curve increases markedly with temperature.

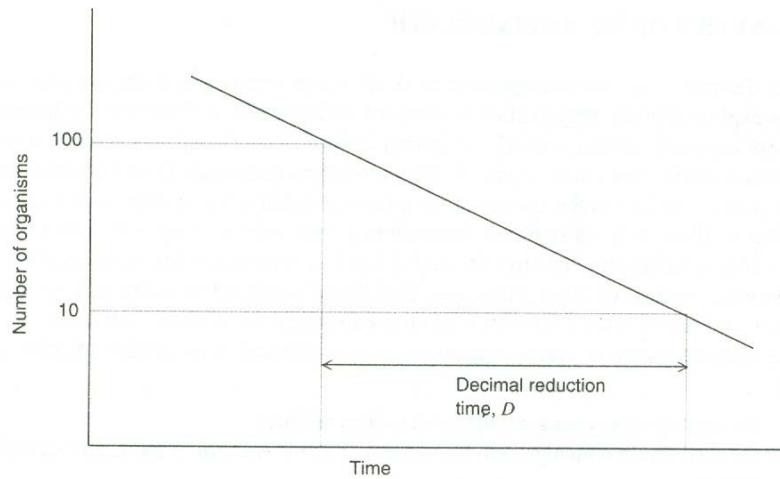


Fig.32.1 Survivor curve

The decimal reduction time  $D$  is defined as the time for a tenfold reduction in the number of survivors of a given micro-organism, in other words the time for one log cycle reduction in the microbial population. Higher values of  $D$  imply, at a given temperature, greater resistance of micro-organisms to thermal death. Because  $D$  depends upon temperature, the temperature in  $^{\circ}\text{C}$  is appended as a subscript. Thus  $D_{121.1}$  is the time required at  $121.1^{\circ}\text{C}$  to reduce a microbial population by 90%. A temperature of  $121.1^{\circ}\text{C}$  (or  $250^{\circ}\text{F}$ ) is used as a common reference point and therefore, because of its importance, this is sometimes referred to as  $D_0$ .

The logarithmic decline in the number of organisms  $n$  is represented by

$$\frac{dn}{dt} = -kn$$

where  $k$  is a rate constant. Therefore the equation of the line in survivor curve is represented by

$$t = D(\log n_1 - \log n_2) \text{ or}$$

$$t = D \log \left( \frac{n_1}{n_2} \right)$$

where  $n_1$  and  $n_2$  are the initial and final number of micro-organisms, respectively. The value of  $D$  is independent of the initial population of microorganisms.

### Example

A sample of fixed volume was held at a constant temperature and the number of microorganisms in the sample measured as a function of time. Calculate the decimal reduction time.

| Time (min) | Number of micro-organisms |
|------------|---------------------------|
| 1.0        | $2.00 \times 10^5$        |
| 2.0        | $4.31 \times 10^4$        |
| 4.5        | $6.32 \times 10^3$        |
| 6.0        | $2.00 \times 10^3$        |
| 7.5        | $6.32 \times 10^2$        |

**Sol:** A plot of the natural logarithm of the number of organisms against time gives a straight line of gradient 3 min. Hence  $D = 3$  min.

The concept of decimal reduction time allows the probability of the survival of spores to be predicted. For example, if a process is sufficiently effective to produce 10 decimal reductions in the microbial population then, if a canned food which is to be sterilised contained initially  $10^{10}$  spores per can, the final population would be one spore per can. Alternatively, for an initial population of  $10^5$  spores per can, the final population would be  $10^{-5}$  spores per can. This latter figure is interpreted to mean that one can in  $10^5$  is likely to contain a spore. Such a process is referred to as a **10D process**.

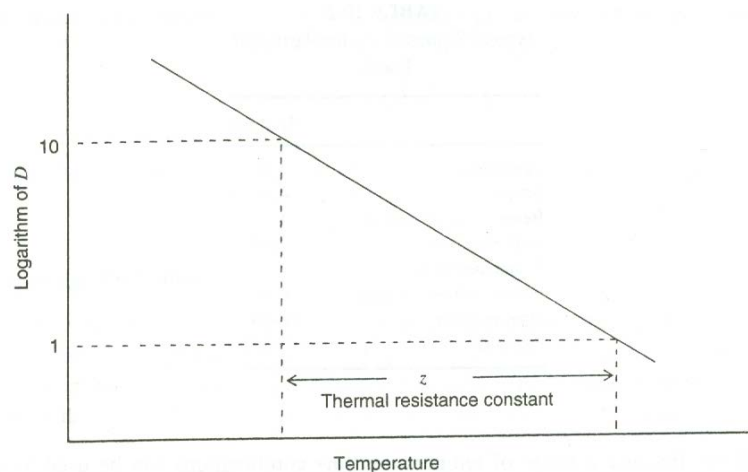


Figure 32.2 Thermal resistance curve.

A plot of the logarithm of decimal reduction time against temperature is generally linear. This is known as a thermal resistance curve (Figure 32.2) from which a thermal resistance constant, or more commonly a  $z$  value, can be defined. **The  $z$  value is the temperature change for a ten-fold change in decimal reduction time  $D$**  and larger  $z$  values indicate greater heat resistance to higher temperatures. Thus, for an organism for which  $z = 13$  K, an increase in

temperature of 13 K will produce a decrease in the decimal reduction time of 90%. For *clostridium botulinum* the value of  $z$  is 10K. The characterization of the kinetics of microbial death in terms of decimal reduction time and thermal resistance constant is the first step in specifying a sterilization process.

### Process Lethality

Having established a method of describing microbial death rates it is necessary to find a way of characterizing a sterilization process so that its effectiveness for any given application can be judged. Because a range of temperature/time combinations can be used to achieve the same reduction in population of a given micro-organism, different sterilization processes can be compared using a quantity known as total process lethality,  $F$ , which represents the total temperature/time combination to which a food is subjected. Less commonly this is called **thermal death time**.

$F$  is the time required (usually expressed in minutes) to achieve a given reduction in a population at specified temperature. For example, a process lethality of  $F = 2.5$  implies heating for two and a half minutes at the reference temperature and for a specified  $z$  value. The reference temperature is usually appended as a subscript and the  $z$  value as a superscript giving, for example,  $F_{121.1}^{10}$ . These particular conditions are used as a reference value of  $F$  which is designated as  $F_0$ .